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A Digital Spiked Shoes for Triaxial Force Measurement using Trigone Frustum and PVDF

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Abstract: In the track and field, the gain sprint and hurdles athletes' stride frequency, support time and vacate time, force size and other technical data are important. This study presents digital spiked shoes for measuring the triaxial force between the shoes and the racetrack during the sprint or hurdle. The shoes consists of instrumented spikes, data acquisition circuits and data storage modules. The instrumented spike is a triaxial transducer, which is a cylinder in diameter 26 mm × height 10 mm and a weight of only 14 g and it is designed and fabricated with a novel mechanical structure using the trigone frustum and PVDF. The shoes are tested by a dynamic test equipment to simulate the impact on the foot-ground interface. The preliminary results agree with the theoretical analysis based on the nonlinear model of the dual systems of impact machine. The starting test was done by a healthy subject from starting block and the data show that the spiked shoes can be used for sport analysis.

Key words: Spiked shoes, triaxial force, trigone frustum, PVDF, starting

INTRODUCTION

The plantar forces provide necessary information to detect in the athletic training; it is need to simultaneously measure triaxial forces under the foot (Kaufman *et al*., 1999). Especially, plantar shear stresses are believed to play a major role in athletic training, a variety of methods have been developed for the measurement of shear stress. A transducer had been designed to measure shear stress (Tappin *et al*., 1980). Therefore, in the study of the forces acting on the plantar surface of the foot the fact that the foot experiences triaxial forces should not be disregarded. Due to the lack of commercial devices that can measure plantar triaxial forces, a number of models have been developed to predict plantar frictional forces (Yavuz *et al*., 2007).

The prototype measured the shear stress locally beneath the metatarsal heads and heel (Hosein and Lord, 2000; Lord and Hosein, 2000). Then Veltink *et al*. (2005) used of two six-degrees-of-freedom force and moment transducers under each shoe, which enables the ambulatory measurement of ground reaction forces and centers of pressure.

A triaxial transducer to measure forces at prosthetic interfaces was 4.9 mm thick with an overall diameter of 16 mm (Williams *et al*., 1992). A triaxial force transducer utilizing four coils, one for excitation and the other three for sensing, embedded into a rubber insole (Warren-Forward *et al*., 1992). However, the development of this transducer was not progressed for clinical use.

Piezoelectric copolymer materials have been successfully used in developing in-shoe vertical force transducers (Nevill, 1991), biaxial shear transducers (Akhlaghi, 1995) and triaxial pressure and stress transducers at the University of Kent (Razian and Pepper, 1998, 2003). An in-shoe triaxial pressure transducer was developed by utilizing piezoelectric copolymer with the mixed composition of PVDF (Razian, 2000). However, the in-shoe gathering system is no suitable for sports movement.

The movement information of athlete is significant for athlete training performance. As for sprint and hurdles athletes, the triaxial forces of the insoles are especially crucial. In this study, the portable spiked shoes is designed for measuring the triaxial forces between the shoe and ground the triaxial interaction force and the portable spiked shoes were tested in starting experiment.

MATERIALS AND METHODS

PVDF material: PVDF (polyvinylidenefluoride) is a semicrystalline piezoelectric polymer with approximately 50-65% crystallinity (Eberle *et al*., 1996). Loading force of PVDF can produce charge. The PVDF film is provided by Measurement Specialties Inc and it is dielectric constants d = 25pC/N.

Transducer mechanical design: The developed transducer consists of three separate transducer elements implemented from commercial PVDF material.

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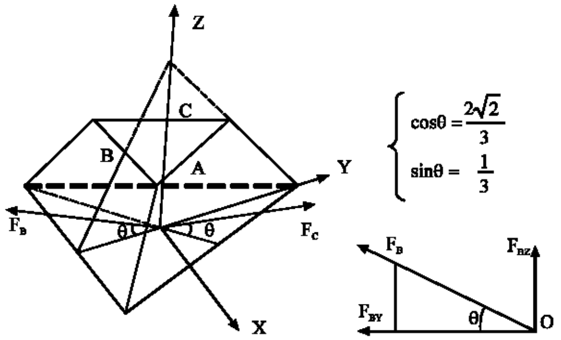

Fig. 1: Theoretical analysis of triaxial force

The vertical and shear force components are separated from the measured signals computationally.

We can now use trigone frustum elements in triaxial forces analysis. A trigone frustum is a frustum made by chopping the top off a tetrahedron. It is a special case of a prismatoid. Take trigone frustum bottom surface equilateral triangle center as the triaxial coordinate system center, Z the axis is the vertical bottom surface direction. The definitions of trigone frustum's three sides are named A, B, C. Establishes the force vertical three surface directions is F_A, F_B, F_C. Subscript A, B, C denotes the three planes. Then, these forces were resolved into its components in the coordinate system, defined origin at the trigone frustum's bottom center (Fig. 1).

The triaxial forces are calculated as expressions Eq. 1-4.

The force resolution for X, Y, Z directions in the Plane-A, is presented in the following F_{AX}, F_{AY}, F_{AZ}.

$$\begin{aligned} F_{AX} &= F_A \cos\theta \cos 30° = \frac{\sqrt{6}}{3} F_A \\ F_{AY} &= F_A \cos\theta \sin 30° = \frac{\sqrt{2}}{3} F_A \\ F_{AZ} &= F_A \sin\theta = \frac{1}{3} F_A \end{aligned} \tag{1}$$

The force resolution for X, Y, Z directions in Plane-B and Plane-C reference subscript denote: F_{BX}, F_{BY}, $F_{BZ,}$ F_{CX} ,F_{CY}, F_{CZ}. They are presented in the following Eq. 2 and 3.

$$\begin{aligned} F_{BZ} &= F_B \times \sin\theta = \frac{1}{3} F_B \\ F_{BY} &= -F_B \times \cos\theta = -\frac{2\sqrt{2}}{3} F_B \\ F_{BX} &= 0 \end{aligned} \tag{2}$$

$$\begin{aligned} F_{CZ} &= F_C \sin\theta = \frac{1}{3} F_C \\ F_{CY} &= F_C \cos\theta \sin 30° = \frac{\sqrt{2}}{3} F_C \\ F_{CX} &= -F_C \cos\theta \cos 30° = -\frac{\sqrt{6}}{3} F_C \end{aligned} \tag{3}$$

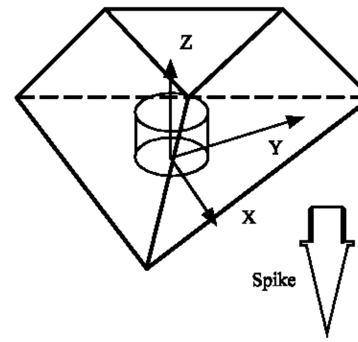

Fig. 2: Definition of triaxial force coordinates in trigone frustum center

The triaxial force in the bottom center and consist of X, Y, Z directions. The situation can be handled conveniently by equations as follows Eq. 4:

$$\begin{aligned} F_X &= F_{AX} + F_{BX} + F_{CX} = \frac{\sqrt{2}}{2}(F_A - F_C) \\ F_Y &= F_{AY} + F_{BY} + F_{CY} = \frac{\sqrt{6}}{6}(F_A - 2F_B + F_C) \\ F_Z &= F_{AZ} + F_{BZ} + F_{CZ} = \frac{\sqrt{3}}{3}(F_A + F_B + F_C) \end{aligned} \tag{4}$$

Several forces parameters in space (X, Y and Z) were calculated on the basis of the force data (F_A, F_B, F_C). The three individual force components were used to calculate the total horizontal and vertical forces. When Plane-A and Plane-C both sides stress are equal, is zero with joint forces. Triaxial forces coordinate axis diagram:

Spike in the center section as shown in Fig. 2. In practical applications, spike was tight in the bottom center.

PVDF elements with lead attachment: The desired performance of a transducer within its operating environment determines its design requirements and characteristics. This transducer is capable of simultaneously measuring three orthogonal forces under any location of the force transferring trigone frustum and force groove base utilizing three element piezoelectric copolymer PVDF. Thus, within the context of athletes running and the in-shoe environment, the required triaxial transducer parameters were investigated and specified in the following (Fig. 3).

The physical design of the transducer element trigone frustum (Fig. 3b, c) is covered by groove base (Fig. 3a). PVDF films are pressed by trigone frustum in the groove base's incline and the low noise two core cable draws out from via hole. The bolt passes through package washer and fastening with the groove base bolt holes. Spike installs in the trigone frustum base (Fig. 4).

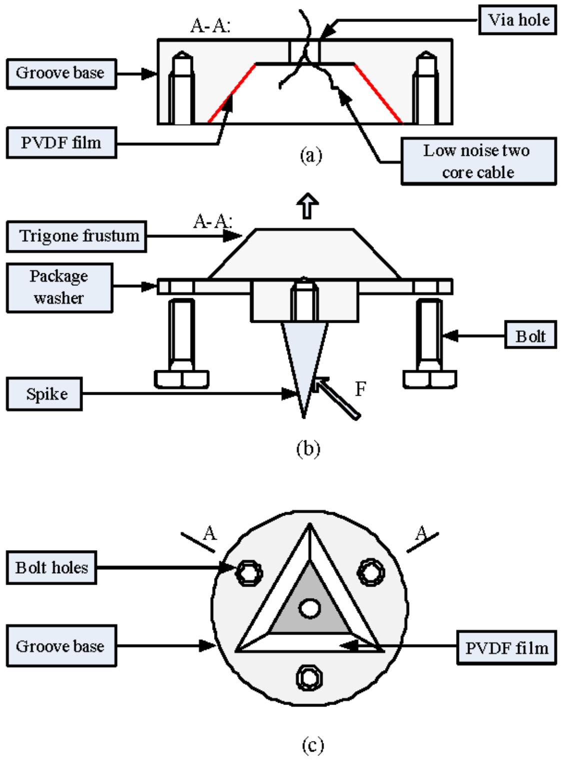

Fig. 3: Transducer elements assemble as (a) groove base (b), (c) trigone frustum

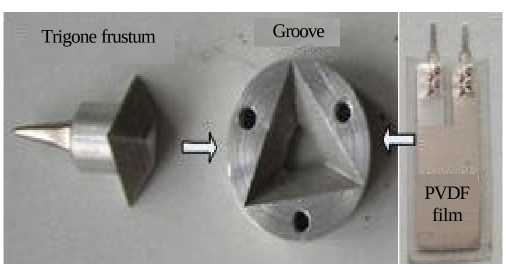

Fig. 4: Force transferring trigone frustum and groove base

A scheme of the spike transducer is shown in Fig. 4. Spike transferring force to trigone frustum.

SYSTEM TEST

In order to test the above-mentioned triaxial transducer we have designed a testing platform for simulation impact on the foot-ground interface. The testing objective is obtains the relations which triaxial transducer's output voltage signal with to withstand the impact load and through comparison the calculated value of dualistic impact system, to confirm the design of spikes transducer availability.

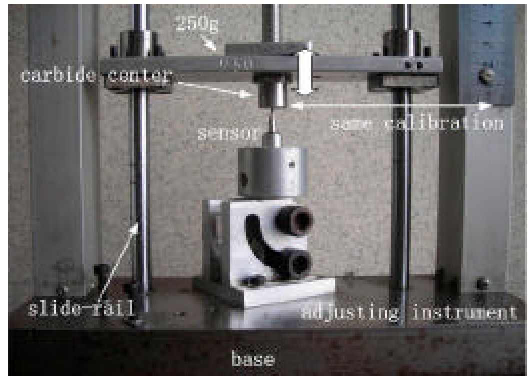

Fig. 5: Dynamic load platform specialized to simulate the impact on the foot-ground interface

Measurement of dynamic load: The structure of dynamic load platform shown in Fig. 5, including the support to fixed transducer, the stainless steel slide-rail and the division aluminum alloy support with scale. The two stainless steel slide-rails maintain the weights and the transducer hit in carbide center. The transducer position may move by adjusting instrument.

The experiment is through the weights which drop along the stainless steel slide-rail hits transducer with fixes on adjusting instrument, causes the transducer to produce voltage signal with relation the hit instantaneous impulse. Because of the impulse is related weights initial altitude, adjusts the weights initial obtain the corresponding voltage signal in the transducer, thus obtains transducer's force-voltage response curve.

In this experiment, the weights most greatly vertical descent height is 9 cm. If we do not consider that weights energy loss which drops along the slide-rail, then 0.25 kg weights drop to the slide-rail bottom obtain the momentum are:

$$mv = m \times \sqrt{2gH_0} = 0.332\ \text{kg} \cdot \text{m sec}^{-1} \tag{5}$$

The supposition transducer undergoes the impact duration (T) that magnitude is about 100 μs and weights final velocity is zero after hit. According to the law of momentum conservation, the transducer receives the impulse (F) and the weights dropped to the slide-rail bottom obtain the momentum the relational expression as:

$$FT = mv \tag{6}$$

By the above equation estimate, the dynamic load platform may obtain the maximum impact is 3320 N, is bigger than 3000 N which the transducer range requests and leaves leeway the remainder.

Triaxial transducer force- voltage characteristic computation: Along the slide-rail dropping weight impact with the transducer process, can be seen as a binary shock system, in which weights as punch hammer, spikes as elastic rod, installed in the spikes of the PVDF film group as the actuating medium. By adjusting the weights of the decline in height, with different weights impact the spikes. By adjusting the weights of the decline in height can produce different speeds. According to kinematics law that the free height of fall (H) and weight velocity (v_2) relations:

$$v_2 = \sqrt{2gH} \tag{7}$$

By nonlinear model considered that hammer with the rod impact causes partially stress variation, according to the Hertz law Eq. 8:

$$\begin{cases} F = (y/h)^{3/2} \\ h = \sqrt[3]{\dfrac{9}{16}\left(\dfrac{1-\mu_1^2}{E_1} + \dfrac{1-\mu_2^2}{E_2}\right)^2 \left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right)} \\ y = u_1 - u_2 \end{cases} \tag{8}$$

As well as consideration the Hunter's maximum extrusion proposed approximate Eq. 9.

$$y / y_{max} = \sin(\frac{1.067 v_0}{y_{max}} t) \tag{9}$$

Transmits in the PVDF thin film group through the spike the force with the hammer speed v_2 relations can be expressed as Eq. 10.

$$F = \left(\frac{y_{max} \times \sin\left(\dfrac{1.067 \times v_2}{y_{max}} \times t\right)}{h} \right)^{\frac{3}{2}} \tag{10}$$

One of them u_1, μ_1, E_1, R_1 and u_2, μ_2, E_2, R_2 respectively is the weights and the spikes of the displacement, Poisson's ratio, Young's modulus and impact local radius of curvature (Zhu, 2003). In the computation takes: $\mu_1 = \mu_2 = 0.3$: $E_1 = E_2 = 200$ GPa; The R_2 radius of curvature produces in the transition of machine-finishing. This study takes R_2 = 0.42 mm. Because the impact surface of hammer is the plane, the hammer radius of curvature R_1 trend is just to positive infinite. Substitution Eq. 8 and got $h = 4.97\times10^{-7}$. y_{max} is the weights and spikes' maximum relative displacement and got y_{max} = 0.06 mm. According to the Eq. 5, 6, 7 and 9 can obtain a theoretical relations between the transducer's output voltage U and the weights decline H:

Table 1: Transducer output for different height H

Weights initial altitude (m)	Force (N)	Voltage (V)
0.005	184.4	1.1
0.01	368.9	2.1
0.015	553.3	2.9
0.02	737.7	3.9
0.025	922.1	4.8
0.03	1106.5	5.7
0.035	1290.8	6.9
0.04	1475.2	7.6
0.045	1659.6	8.8
0.05	1844.4	9.1
0.055	2028.4	10.9
0.06	2212.8	12.3
0.065	2397.2	12.1
0.07	2581.6	12.8
0.075	2766.0	13.1
0.08	2950.4	13.5
0.085	3134.8	14.3
0.09	3320.0	13.8

$$U = \frac{d}{C} \left(\frac{y_{max} \times \sin\left(\dfrac{1.067 \times \sqrt{2gH}}{y_{max}} \times T\right)}{h} \right)^{\frac{3}{2}} \tag{11}$$

where, d is the piezoelectric constant of the PVDF film (d = 25 pC/N), C is the feedback capacity of the charge amplifier (C = 10000 pF), T is impact time between the weights and the spike that is obtained by the oscilloscope survey (T = 100 μs). Then put them into the Eq. 11 and draws up the output characteristic theoretical curve as described in Fig 7.

Test result and analysis: Transducer output signal show variation with the different impulse. They are stored in the SD card after AD transformation. The weights along the slide-rail's dropping vertical separation are 0.005 m and increases gradually to 0.09 m. Each altitude tests three times then we recording parameters in the comparison Table 1.

In Fig. 6 is separated the diamonds spot is the experiment data, closely spot expression according to Eq. 11 theoretical calculation result.

Figure 7 is relationship between force and voltage. The point regulation linear distribution in the measuring range, it confirms the spike transducer design rationality and the usability. Under the analysis of Eq. 11, if any further expand the transducer's measuring range, may through increase parameter y_{max} as well as reduce parameter T to realize. Parameter y_{max} will be decided by spike's motion space and the machine-finishing precision; y_{max} increases will cause the impact effect time T extension. At the same time, selects the different material manufacture spike and hammer can affect parameter h and then affects the spike transducer output voltage dynamic range. The h reflects the spikes and the weight of the

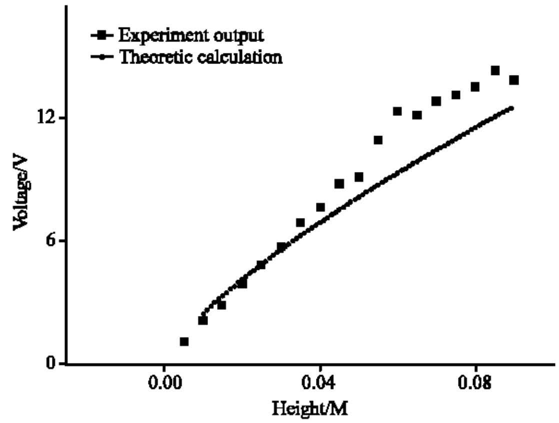

Fig. 6: Comparison output curve between the experiment and the theoretic calculation

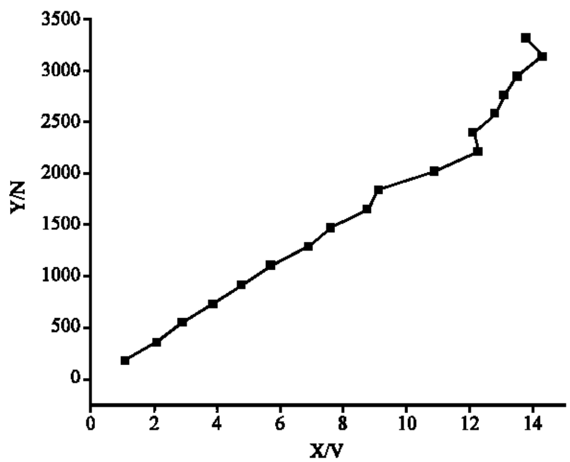

Fig. 7: The relationship between spikes force and voltage

mechanical properties parameters, in practical applications also need to consider the different racetrack characteristic parameters.

STARTING EXPERIMENT

A preliminary spike shoes force measurement with the developed triaxial transducer was carried out. These transducer locations were chose in medial and lateral metatarsal heads. Then, an 8 mm thick gouge was notched on the spike shoes' insole to contain triaxial transducer. The triaxial transducer was assembled on spike shoes' floor with bolts and washers. High speed signal acquiring system was taped on instep by shoelace (Fig. 8).

Force of three PVDF films of the starting were measured with a healthy subject (27-years-old male, height 180 cm and body mass 73 kg). Each PVDF film was measured separately. The measurement was done by starting from starting block (Fig. 9).

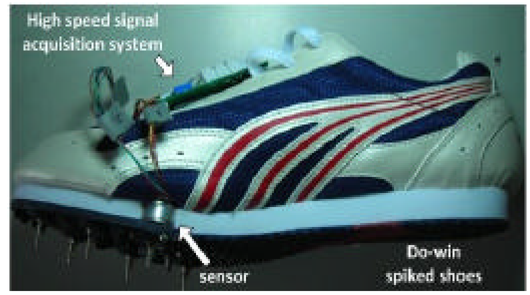

Fig. 8: The spiked shoes with triaxial transducer and high speed signal acquiring system

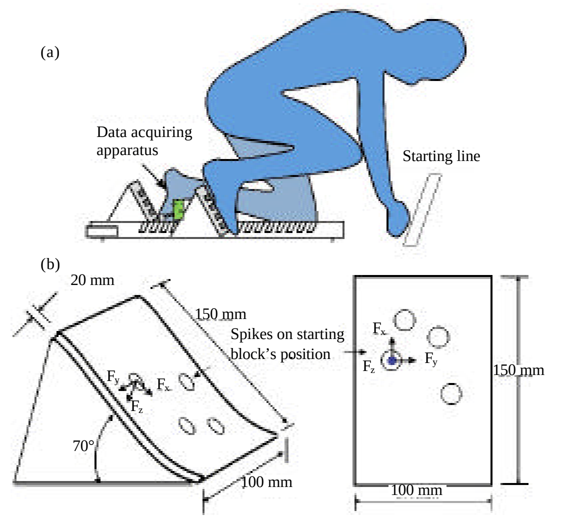

Fig. 9: (a) Starting experimental setup and (b) Spikes on starting block's position and the direction of triaxial force

The results show that the direction of F_A, F_B, F_C are obtained by this spike shoes (Fig. 10). The number of each graph shows the number of F_A, F_B and F_C of experiment. A horizontal axis expresses the time. A vertical axis expresses the voltage. A force-voltage ratio is the value which broke starting block reaction force by the subject's weight.

Using the above mentioned data, we obtain the F_A, F_B and F_C. Then, the F_X, F_Y, F_Z can be calculated and obtained by Eq. 4, the results are as follows:

$$F_X = \frac{\sqrt{2}}{2}(F_A - F_C) \approx 0.71(F_A - F_C) = 376.3\text{N}$$

$$F_Y = \frac{\sqrt{6}}{6}(F_A - 2F_B + F_C) \approx 0.41(F_A - 2F_B + F_C) = 340.3\text{N}$$

$$F_Z = \frac{\sqrt{3}}{3}(F_A + F_B + F_C) \approx 0.58(F_A + F_B + F_C) = 864.2\text{N}$$

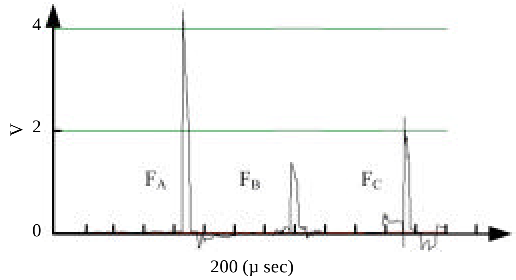

Fig. 10: Original data F_A, F_B, F_C

Figure 10 may promote the direction of triaxial force, F_Z and F_X composed together starting the power forward. And we observes some athletes starting the video recording and find the athletes body is swinging in the starting, this may explain F_Y produces reason. Despite of the promising results obtained in this study, the developed transducer is only a preliminary prototype.

CONCLUSION

In this study, a novel mechanical structure with a type of trigone frustum and groove is designed, calibrated, then the shoes based on it were used for recording the triaxial forces in starting experiment. The results show that the spiked shoes have the sufficient accuracy and fast response to acquire triaxial forces data of the discrete spikes. The triaxial forces of spiked shoes are important for the running information analysis between the ground and the spiked shoes. In our future work, the shoes designed will be used for the sports application such as track and field events.

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REFERENCES

Akhlaghi, F., 1995. An in-shoe biaxial shear force transducer utilizing piezoelectric copolymer film and the clinical assessment of in-shoe forces. Ph.D. Thesis, University Kent at Canterbury, Kent, UK.

Eberle, G., H. Schmidt and W. Eisenmenger, 1996. Piezoelectric polymer electrets. IEEE Dielectrics Electrical Insulation Trans., 3: 624-646.

Hosein, R. and M. Lord, 2000. A study of in-shoe plantar shear in normals. Clin. Biomech., 15: 46-53.

Kaufman, K.R., S.K. Brodine, R.A. Shaffer, C.W. Johnson and T.R. Cullison, 1999. The effect of foot structure and range of motion on musculoskeletal overuse injuries. Am. J. Sports Med., 27: 585-593.

Lord, M. and R. Hosein, 2000. A study of in-shoe plantar shear in patients with diabetic neuropathy. Clin. Biomech., 15: 278-283.

Nevill, A.J., 1991. A foot pressure measurement system utilizing PVDF and copolymer piezoelectric transducers. Ph.D. Thesis, University of Kent Canterbury, Kent, UK.

Razian, M.A. and M.G. Pepper, 1998. A novel triaxial force transducer for in-shoe and other biomechanical applications. J. Biomechan., 31: 133-133.

Razian, M.A. and M.G. Pepper, 2003. Design, development and characteristics of an in-shoe triaxial pressure measurement transducer utilizing a single element of piezoelectric copolymer film. IEEE Trans. Neural Syst. Rehabilitation Eng., 11: 288-293.

Razian, M.A., 2000. A miniature piezoelectric triaxial force transducer and a novel charge multiplexing technique for biomedical applications (gait analysis). Ph.D. Thesis, University Kent at Canterbury, Kent, UK.

Tappin, J.W., J. Pollard and E.A. Beckett, 1980. Method of measuring shearing forces on the sole of the foot. Clin. Phys. Physiol. Meas, 1: 83-85.

Veltink, P.H., C. Liedtke, E. Droog and H. van der Kooij, 2005. Ambulatory measurement of ground reaction forces. IEEE Trans. Neural Syst. Rehabilitation Eng., 13: 20-26.

Warren-Forward, M.J., R.M. Goodall and D.J. Pratt, 1992. Three-dimensional displacement and force transducer. Proc. Inst. Elect. Eng., 139: 21-29.

Williams, R.B., D. Porter, V.C. Roberts and J.F. Regan, 1992. Triaxial force transducer for investigating stresses at the stump/socket interface. Med. Biol. Eng. Comput., 30: 89-96.

Yavuz, M., G. Botek and B.L. Davis, 2007. Plantar shear stress distributions: Comparing actual and predicted frictional forces at the foot ground interface. J. Biomechanics, 40: 3045-3049.

Zhu, P.Y., 2003. Study of Dynamic Inverse Design Method on Impact Machines [D]. Hunan: College of Mechanical and Electrical Engineering of CSU, London.