

# **In-shoe Measurement for Biomechanical Monitoring**

by

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## **Abstract**

The purpose of the research is to investigate the measurement and characterisation of biomechanical variables associated with ground contact during the course of athletic activity (e.g., running). The measurement approach will involve the appropriate instrumentation of a shoe insole, which lies between the foot and the shoe bed, using MicroElectroMechanical Structure (MEMS) based sensors. The information obtained from the insole could be used to quantify training stress and competition demands which will greatly assist in enhancing athletic performance. This research will be carried out between the years of 2001 and 2004, under a collaboration between the Industrial Research Institute of the Swinburne University of Technology (IRIS), the Australian Institute of Sport (AIS) and the Cooperative Research Centre (CRC) for MicroTechnology.

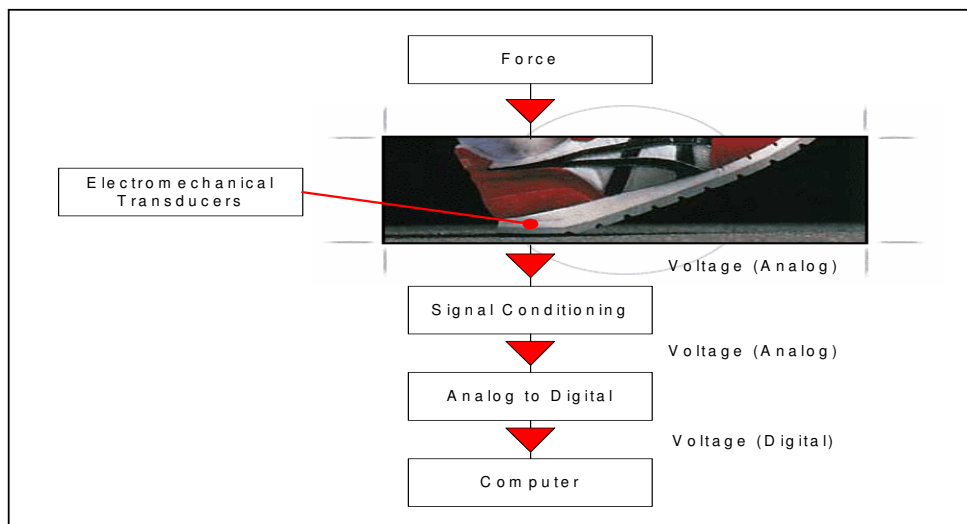
## **1. Introduction**

Movements of the human musculoskeletal system are produced by the contraction of muscles and are moderated by environmental factors such as gravity, friction, wind resistance and the so-called normal reaction forces through contact with the ground. The resulting movements thus depend on two sets of factors – those that influence the muscular contraction itself and those that influence the moderating effects of the environment. The study of the factors that influence the moderating effects of the environment lies within the branch of physics known as mechanics or more specifically biomechanics. As an athlete's only means of evoking force from muscular contraction for running is through foot contact with the ground this interaction is of special interest and significance.

The feet form the human body's force transfer interface and offer more leverage for improving athletic performance than any other part of the body (Bates, Osternig & Sawhill, 1983). Within the complex structure of the foot there are a combination of 38 muscles, 52 bones, 66 joints, 224 ligaments and a network of tendons, nerves, and blood vessels that all work together to balance, support and propel the body. Footwear serves as an inter-interface between the foot and the ground and has undergone extensive development over the past decade through a greater understanding in this role.

Given the importance of the interaction between the human body and the ground, a great variety of methods, both contact and non-contact, have been used during the past century to characterise and measure activity from one or more of four different interfaces – between the barefoot and the ground, between the foot and the shoe insole, from within the shoe sole, and between the shoe outsole and the ground.

The particular method to be investigated in this research is the use of an instrumented shoe insole, containing appropriate electromechanical transducers, applied to the foot-shoe interface. Transducers used in this form of measurement are generally termed contact electromechanical transducers and convert the energy associated with impact into electrical output for convenient data acquisition by computers. That is, electromechanical transducers produce a change in electrical properties when subjected to mechanical loads (Fig. 1). The major advantages of using an instrumented insole is that the measurement device travels with the athlete, may be applied with minimal disruption to preexisting conditions, and this form of instrumentation provides the ability to measure a number of biomechanical performance measures simultaneously, as outlined in Section 3.



**Figure 1: Illustration of the Process from the Onset of Force at Ground Contact to Data Transfer to a Computer.**

## 2. Industrial Implications

The development of an instrumented insole to simultaneously measure a range of biomechanical variables will enable unprecedented characterisation of training stress and competition demands. For example, it is known that with fatigue, the impact forces begin to increase and the foot remains in contact with the ground for longer. This could lead to injury. The ability to monitor such variables simultaneously in real time will

allow scientists at the Australian Institute of Sport to determine the onset of a fatigued state.

The application of the instrumented insole within the sporting sector and other allied fields such as the military, health, and medical rehabilitation industries provides a strong commercial potential.

### 3. Biomechanical Variables

#### 3.1 Overview

For ease of explanation, the mechanics of running can be described by two distinct branches of biomechanics - kinematics and kinetics. Kinematics refers to the description of motion and common quantities used are distance, velocity, and acceleration. Kinetics, however, describes why a body moves in the way it does and common quantities include force, pressure, mass, momentum, impulse, friction, and power. Within both branches of biomechanics there exist a number of interdependent performance measures and their simultaneous measurement significantly enhances the value of the insole measurement device. The interdependency between the kinematic and kinetic quantities and the target measurement variables are illustrated in Figure 2.

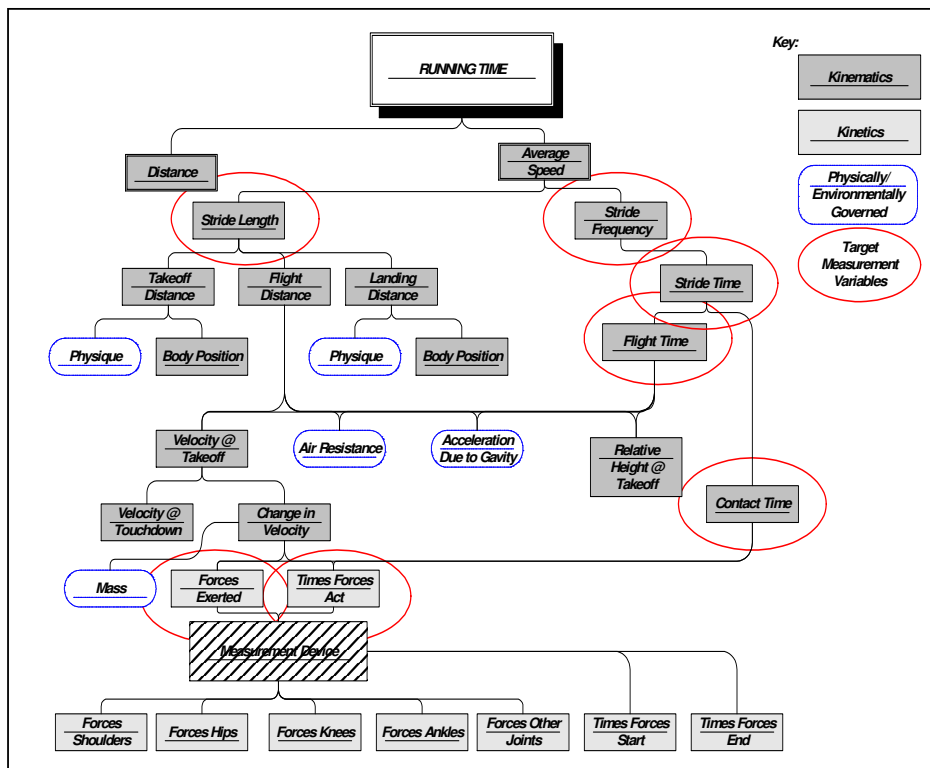


Figure 2 - Model flowchart of basic biomechanical factors in running and target measurement variables (Adapted from Hay, 1993).

### 3.2 Kinematics

As illustrated in Figure 2 the target kinematic variables include:

- Stride Length – distance covered with each stride
- Stride Frequency – the number of strides taken in a given time
- Contact Time – the time the foot is in contact with the ground
- Flight Time – the time in which there is no contact with the ground

Running speed is the product of stride length and stride frequency (Figure 2). If a runner can improve one or both they will reach the finish line faster. However, these two variables are interdependent and their optimisation is the key to improved performance. The sum of contact time and flight time equals stride time which is the determinant of stride frequency. Kinematics describe the motion of the athlete and their simultaneous measurement allows a detailed understanding of performance in a race.

Stride frequency, contact time, and flight time may be determined directly from within the shoe insert using suitable electromechanical transducers. As described in Section 4, early work has concentrated on the characterisation of these measurement variables. Stride length is a much more complex parameter and will require additional instrumentation of the shoe insert. To accurately measure stride length the linear displacement from one foot fall to the next is required, however the foot does not move in a linear fashion. Early indications suggest that a potential solution to determine the three dimensional translation of the foot may be in the form of a dead (deductive) reckoning device incorporating three axis accelerometers, gyroscopes and magnetometers.

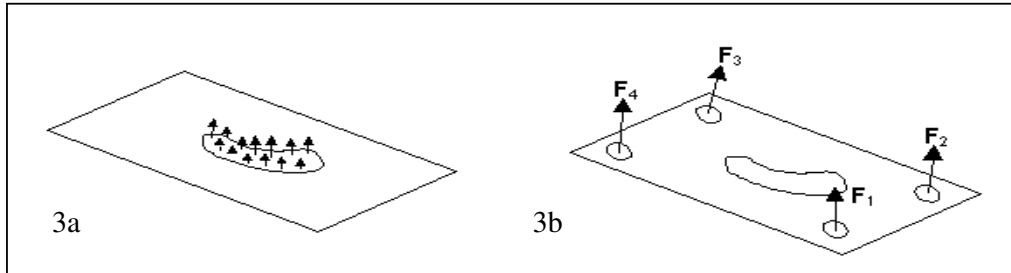
### 3.3 Kinetics

Foot contact generates a reaction force from the ground. This reaction force is distributed under the plantar surface of the foot and its effect is to accelerate individual body segments and transmit force to adjacent segments. Figure 3a illustrates the reaction force vectors acting on small areas of the foot. Plantar pressure measurement techniques offer a visual description of how these forces are distributed under the foot as well as providing quantitative information about the timing and loading of individual foot structures. However, plantar pressure distribution does not provide information regarding the non-planar forces which may be applied by the foot. A force platform measures the resultant ground reaction force (GRF) (Figure 3b) that may be partitioned into three components acting at right angles (vertical, anterior-posterior, medio-lateral) which change in magnitude, direction, and point of application during the course of support. However, measurement of GRF with a force platform does not provide information regarding the force distribution over the individual structures (e.g., Figure 3b) of the foot and incorporates many measurement constraints as the measurement device does not travel with the athlete.

An insole that can measure the magnitude, direction and point of application of the resultant force and determine the way in which this is spatially distributed over the plantar surface of the foot would enable unprecedented characterisation of kinetic variables in the training and competition environment.

Target kinetic variables include:

- Foot strike and plantar pressure distribution patterns
- Direction and magnitude of applied force by the runner



*Figure 3 - Reaction force vectors acting on small areas of the foot (a) and the reaction force vectors acting on the four corners of a force plate (b).*

#### 4. Insole Measurement Considerations

Depending on the direction and point of application, forces can produce tension, compression, bending, shear, friction and torsion at the foot-shoe interface. Furthermore, it is logical to assume that the foot-shoe interface is subject to a sum of these different stresses simultaneously. Plantar pressure measurement techniques provide an indication of compression forces between the foot and the shoe bed but do not provide the full representation of the active forces. This complex force pattern is a result of the changing geometry or deformation of the mediating structures surrounding the insole throughout the support phase. This suggests that the analysis of stress distributed across the foot structure is extremely complex, conditional and dynamic in nature and much consideration needs to go into the selection, design and arrangement of appropriate electromechanical transducers.

Because feet exhibit individual variations, the exact placement and arrangement of transducers under the anatomical sites of interest are not accurately known. Furthermore, depending on different shoe construction peculiarities, the relative positioning of an insole measurement system under the foot may vary. To overcome these problems insoles with a high number of small transducers are necessary. The practical reality of measurement using an insole is that the introduction of the device at the foot-shoe interface has the potential to change the characteristics to be measured. Hence, a sufficiently thin and robust sensor is necessary if the geometric characteristics of the surface are to remain unaltered and measurements are to be representative of the foot-shoe interaction. Along with the various force responses that may be encountered

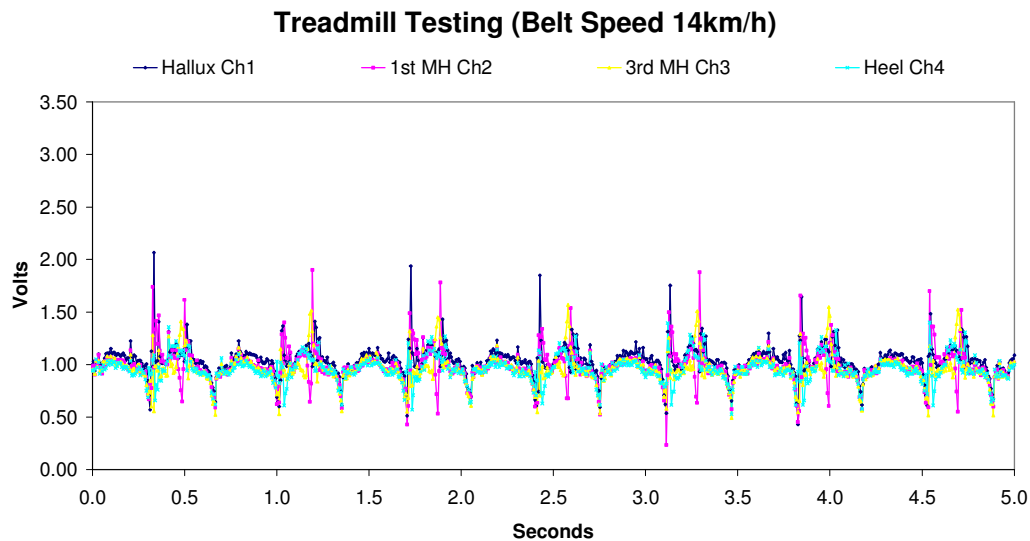
at the foot-shoe interface, human tissues within the foot are capable of absorbing shock and converting it to heat which serves to create a harsh environment (e.g. heat, moisture, humidity) for electromechanical transducers. Appropriate consideration for the encapsulation and protection of transducers is required.

In order to determine various quantitative biomechanical measures from the foot-shoe interface each individual transducer must meet the following requirements: high sensitivity and resolution; large range; static and dynamic frequency responses; linearity; low hysteresis; low creep; and reproducibility. Furthermore, transducer calibration, power requirements and interference issues require consideration.

## **5. Experimental Details & Results**

Initial experimentation has focused on developing a greater understanding of the employment of transducers at the foot shoe-interface on an insole. Custom flexible laminate, polycarbonate insoles have been designed for a specific foot type in order to mount up to four discrete electromechanical transducers. Following from the work of Hennig & Milani (1995), the circuit layout provides transducer terminals at the major anatomical support structures of the foot. Polyvinylidene fluoride (PVDF) transducers have been used in initial experiments. PVDF is a piezoelectric transducer that responds electrically to deformation in its shape. PVDF has many advantages for this application including its structural dimensions (9 $\mu$ m thickness), self-generating function, has high voltage output, high mechanical strength and impact resistance, and may be fabricated into custom shapes.

In order to evaluate the instrumented insole from both a qualitative and quantitative perspective a number of basic running tests have been performed. Figure 4 provides an illustration of typical data, collected in a hard wired form whilst running on a treadmill with a belt speed of 14 kph (3.89m/s). As illustrated in the data some distinct patterns emerge that represent each consecutive foot strike. Stride frequency, contact time and flight time may be readily determined by applying an appropriate pattern recognition methodology. The measurement of force is much more complex and careful consideration must be given to the fact that a PVDF sensor responds not only to forces perpendicular to its surface but also any form of deformation to its original shape (e.g. lateral and axial).



*Figure 4 - Data from the 14 km/h belt speed over a 5 second period using the instrumented insole.*

## 6. Conclusion & Future Work

Significant advances have been made in the development of the surface mount insole. This insole will provide a platform upon which a range of electromechanical transducers are applied and tested. Preliminary research has demonstrated the ability to measure a number of kinematic variables (e.g. stride frequency and contact time), from the instrumented insole, through pattern recognition techniques. Data telemetry capabilities and analysis software are nearing completion which will accelerate the research process and permit specific testing in the training and competition setting. The underlying theme of future work will be the design, development and integration of suitable MEMS transducers for this application.

## 7. Acknowledgments

Bill Filipou of Griffith University has conducted significant work in the development of data telemetry capability and analysis software. The Australian Institute of Sport who have provided significant technical input into the work detailed herein.

## 8. References

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