MEASUREMENT AND EVALUATION OF LOADS ON THE HUMAN BODY DURING SPORTS ACTIVITIES

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INTRODUCTION: For events in most sports disciplines, cinematographic techniques are generally not sufficient to estimate forces and accelerations during short duration impacts. Therefore, mechanical transducers are required to register the accelerations, forces, and pressure distributions that occur during human motion. In this presentation important transducer characteristics will be presented first. Then, specific demands for the recording of forces, accelerations and pressure distributions in biomechanical applications will be discussed.

Transducer Properties: Accelerometers are measuring devices based on the determination of the forces produced by a known mass m. Pressures are calculated from recorded forces across a known area A. The methods for the measurement of forces are based on the effect of changes in the electrical properties of a sensor, caused by the mechanical deformation of its material. Therefore, the elastic response of material deformation plays a major role for the quality of a transducer. Ideally, a transducer should respond to both slow and fast changing mechanical inputs linearly and without phase distortion. The frequency response of a transducer depends upon the type of sensing element, its geometric dimensions and the electronic processing. The natural frequency of a sensor refers to the free oscillation of a fully assembled transducer system when exposed to a short mechanical pulse. The frequency at which a forced sinusoidal oscillation causes the highest amplitude of the vibrating system is called the resonant frequency. Data sheets on frequency response provide information about changes in transducer output, gain or attenuation, across a frequency band. The graphical representation of the frequency response is typically shown on percentile or logarithmic (db) scales. Depending on the quality of force transducers, more or less deviation from an ideal straight line relationship between mechanical input and transducer output will be present. One method to quantify linearity depends on the maximum deviation of the output signal from the best straight line. If no or very little hysteresis is present, unlinearity of a transducer can easily be corrected for by numerical correction, using calibration data. The hysteresis of a transducer describes its response as a function of previous loading history. For a force transducer, it is defined as the largest difference in output between two identical forces during loading followed by unloading. Hysteresis is typically expressed as a percentage of this largest difference towards full scale output. Hysteresis values for rigid and elastic transducers (e.g., piezoelectric force transducers) are low. However, transducers exhibiting large and viscoelastic deformations show substantially higher hysteresis values. Hysteresis is also dependent on the rate of loading and normally increases with higher frequency mechanical inputs. Because loading history and load amplitude influence the shape of the curve, measurement accuracy is substantially reduced in the presence of large hysteresis. In sports activities with short duration impacts, numerical corrections of hysteresis effects are generally not possible. The hysteresis value of a transducer is an important variable for judging its quality as a measuring tool.

Acceleration Measurements: During the contact of the foot with the ground impact shocks are generated. This impact shock can be measured by lightweight accelerometers mounted at different locations (shank, pelvis and head) along the locomotor system. In biomechanics, acceleration is commonly expressed in multiples of g (9.81 m/s^2). Through measurements with bone-mounted transducers, acceleration peaks of more than 5g and 11g have been recorded along the tibia during walking (Lafortune & Hennig, 1992) and running (Lafortune et al., 1995). The spectral analysis of bone signals indicates that accelerometers for use in locomotion should have useful frequencies from DC to a minimum of 100 Hz. The mounting of accelerometers in bone is an invasive technique to measure skeletal acceleration. For most locomotion studies, less traumatic superficial mounting is usually employed. The adequacy of this mounting is heavily dependent upon the technique used to secure the transducer to the bone (Schnabel & Hennig, 1995). Based upon the magnitude of the shock recorded at the tibia, accelerometers with a range of +/- 20 g should be adequate for most locomotion studies. However, many higher peak accelerations may be present for the impacts of body parts in certain sports. Racket-induced wrist vibrations during tennis or tibial accelerations during shooting a soccer ball may well exceed 20g (Hennig et al., 1992). For running in various kinds of footwear, a close relationship between peak tibial acceleration and ground reaction force variables has been reported (Hennig et al., 1993). Using the maximal force rate towards the initial force peak in running, a determination coefficient of r^2=0.95 was found for the prediction of tibial accelerations. Based on these results, force platform measurements are sufficient for the estimation of shock absorbing properties in running shoes.

Measurement of Forces: The recording of forces during sports activities deal primarily with the non-invasive recording of ground reaction forces. In-vivo direct measurements of human achilles tendon tension are rare exceptions (Komi, 1990). To facilitate comparisons between individuals with different body masses, body weight units (BW) are used for normalization purposes. During sports activities, ground reaction force (GRF) peaks have been shown to vary between 1 and 12 time body weight (BW), with contact times from 100 ms to more than one second (Baumann, 1981; McClay et al., 1994). Force platform recordings have been extensively used for running research. The running pattern is characterized by an initial high frequency force peak (1.5-2.5 BW) followed by a second larger (2.0-3.0 BW) but lower frequency force peak. A good compilation of force platform measurement studies for running has been published by Miller (1990). The fast rising GRF and its frequency components challenge force platform mountings. Mountings must consequently be rigid enough not to interfere with the physical characteristics of the platform. Targeting is a major problem in the measurement of GRF. It can be reduced effectively by larger size platforms.

Pressure distribution measurements: Pressure is defined as the force divided by the area on which this force acts. Pressures are measured in kPa (100 kPa=10 N/cm^2). During locomotion the forces between the human body and the ground are distributed under the various supporting structures of the foot. Measurements of ground reaction force with a force platform do not provide information about the loading of these individual structures. In recent years, the availability of inexpensive force transducers and modern data acquisition systems have made possible the construction of various pressure distribution measuring systems. Transducer technologies for pressure distribution devices are based on capacitive, piezoelectric and resistive principles. Typically, discrete pressure sensors are arranged in matrices to provide pressure distribution profiles. Pressure platform resolution is defined as the distance between the centers of adjacent discrete sensors. Resolutions of 2 sensors/cm^2 should be present to obtain detailed information under the fine structures of the feet. Data acquisition, processing and storage are important issues for pressure distribution measurements. For instance, recording durations of one second at a sampling rate of 50 Hz for a pressure mat that comprises 2000 elements will result in 100,000 pressure data points. With this high volume of information, visual presentation and data reduction techniques become important. Graphical representation of pressure distribution is commonly achieved through wire frame diagrams or isobarographs. These pressure maps can be obtained for each sampling interval or at specific instants during the foot-ground contact. A peak pressure analysis provides information about the highest pressures under the foot, as they occur throughout contact (Figure 1).

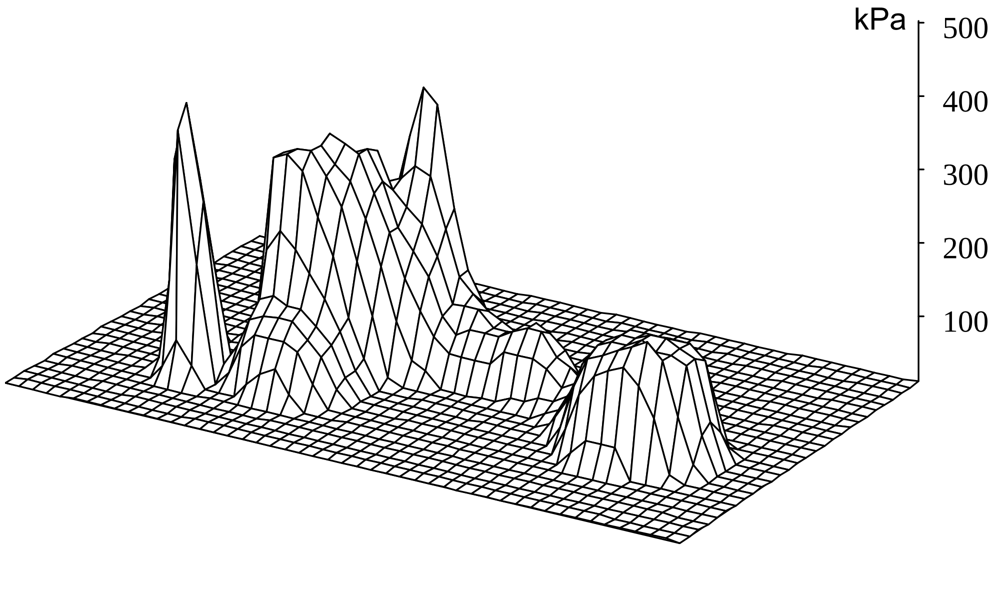

Figure 1: Peak pressure wireframe diagram for barefoot walking (values in kPa)

Because footwear modifies the foot to ground interaction considerably, in-shoe pressure measurements are of special interest. Matrix sensor insoles can easily be placed inside shoes. Because most feet exhibit individual anatomical variations, the exact placement of the sensors under the anatomical sites of interest are not known. Moreover, depending upon shoe construction peculiarities, the relative positioning of the insole matrix under the foot may vary. To overcome these problems, pressure insoles with large numbers of small transducers are necessary. However, pressure insoles with a high density of accurate sensors are expensive, have restricted time resolution and generate large amounts of data. It must also be recognized that a device depending on relatively large deformations of its visco-elastic sensing elements will act as an in-shoe cushioning element. Thus, it will modify the magnitude of the pressure that it attempts to measure. The use of a limited number of discrete rigid transducers offers a viable alternative for gathering in-shoe pressure information. These sensors are fixed with adhesive tape under foot structures that are manually palpated. The major advantage of this technique is an exact positioning of the sensors under the foot structures of interest, independent of individual foot shape. It also guarantees that the sensor locations remain independent of footwear construction peculiarities. These sensors have successfully been used in a number of consumer product running shoe tests (Hennig & Milani, 1995).

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