THE APPLICATION OF BIOMECHANICS METHODOLOGY TO DEFINE DESIGN CRITERIA AND NORMS. SPORTS SURFACES AND SHOES EXAMPLES.

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INTRODUCTION: As a member of a lot of technical European committees for standardisation I have heard many times that biomechanics is quite impractical. Experts in other fields accuse us when they say: "You always find the defects, why aren't the products or test methods perfect, and when we ask how the methods or products can be improved you do not have any real answers." Sometimes our defect as biomechanists is that we explain why things happen but not how to change them. An example of typical biomechanics answer would be the friction of sport surfaces. We always say that low friction produces falls and high friction produces injuries by overload and stress, and that the standard test methods do not accurately simulate people's movement. That is true, but how can friction be measured and what are the limits?. Normally our problem is that we know that the limits for one parameter depend on the kind of people and their level of training. These are not the same for children, men, women or elderly people. It is difficult to take a decision about limits if they are not fixed for a very specific group of people. Perhaps it is easier to customise a shoe for a top athlete than to decide an optimum product for huge markets. However, I do not share the opinion that biomechanics is not very useful for practical questions, such as product improvement or test methods. Biomechanical concepts have been applied successfully in lots of cases, especially in the sports industry. Sport shoes are a typical example. Every-body knows the torsion or shock absorption systems applied by big companies. In the following discussion I will focus on the methodology used in the Institute of Biomechanics of Valencia (IBV) for product assessment, the development of new criteria and test methods. The aim of this methodology is to enable the knowledge that IBV generates applicable at an industrial level. From the very beginning IBV has invested in developing its own measurement equipment, especially in the basics of biomechanics: measurement of forces, movement and pressure. Our scientific work is not limited by any classic biomechanics definition. As we design a lot of our test devices we are not technologically dependent and are able to adapt software and devices to specific cases. And as time passes, we are becoming suppliers of this technology. Our investment does not limit itself to classic biomechanics. This is logical if we want to assess industries, the acceptance of a product used by and which interacts with the consumer does not only depend on biomechanical questions. We try to offer our client the most complete service. For this reason we cover more aspects than simply biomechanical ones. Before talking about the biomechanical aspects of sport equipment, or products in general, it is important to introduce some factors that must be considered when we study any equipment from a biomechanical point of view. These factors are always considered in the research methodology at IBV. We usually refer to three levels in the research process. One: users and equipment, Two: the measurement of objective parameters in movement or work, Three: the effects that the equipment produces on the user, effects like comfort, injuries, pain, etc. The factor levels are classified according to their place in a hypothetical cause-effect chain (Page *et al.*, 1994). Thus, the first level groups the objective values related a consumer profile (gender, age, anthropometric dimensions, category, etc) and those of the material and equipment used. For example of the footwear characteristics (hardness of the sole, midsole and insole, height, etc) or the sports surface (friction coefficient, hardness, etc). As a consequence of a determined combination of factors at this first level, the muscle-skeletal system is subjected to mechanical forces that oblige sportsmen to perform certain postures and movements, this is known as "kinematic adaptation hypothesis" (Nigg *et al.*, 1984; Stucke *et al.*, 1984; Gheluwe and Deporte, 1992). These mechanical parameters and the objective biomechanical response of sportsman constitutes the second level. Finally, as a consequence of this adaptation, the efficiency can be modified. The sportsman experiences situations of discomfort and fatigue both at different points of the muscle-skeletal system and at the psychological level; the sportsman may even suffer if the mechanical demands are too high. This group of factors corresponds to the third level.

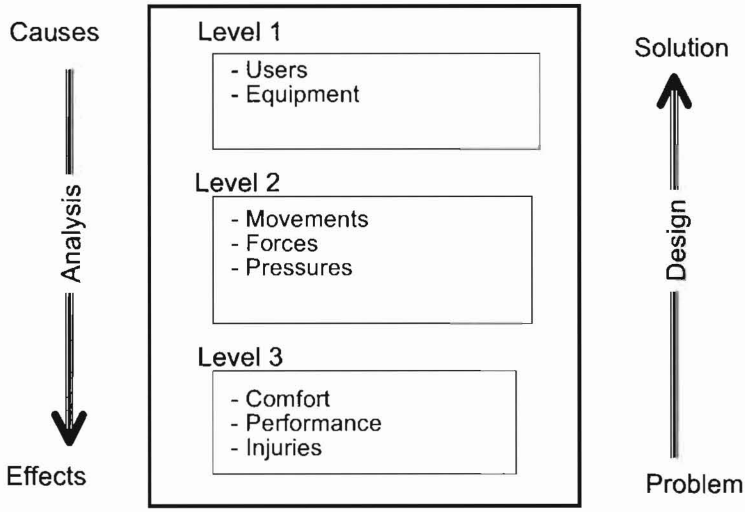

Figure 1. Cause – Effect chain.

Obviously, for the evaluation or research process and to obtain design criteria, the best way is to study all three levels. Anyway in any event we can study only two levels according to the results we are interested in. Of course another important reason to reduce the number of levels is related to the budget. There are different ways for evaluating or studying any given equipment. If we only use level 3 and level 1 we can obtain design criteria based on the consumer's opinion and epidemiological studies. With this method the problem is twofold: firstly we do not know the real reasons for discomfort or injury, for example although the experts may have their suspicions we do not know if one sport surface produces more knee injuries through excess friction or shock absorption. The second problem is that the opinion of the users when classifying products on a single scale, from very bad to very good, is based on the existing equipment at any one moment. If new technology or a new product appears the user's opinion could change. Normally, if we use only level 1 and level 3, it involves plenty of work time and money to establish a broad spectrum of the consumer's opinion. If we use levels 1 and level 2, we can objectively measure the influence of the equipment. In this way we can measure for example if a particular surface increases the impact of the jump or the pressure levels that a seat exerts upon the buttocks. We can classify different equipment and try to define test machines that simulate the effect of peoples' movement. These will reduce the high cost of testing people for future evaluations. Finally with level 3, effects on the user we can establish optimum values for the equipment parameters. In the following we will talk about some examples related to the application of this methodology.

SPORTS SURFACES EXAMPLES: Some years ago we were involved in a research project whose aim was to study the application of existing standard test methods and the criteria for multiuse indoor sport surfaces. In that case level 1 was player's dimension, training level, movement pattern, surface mechanical characteristics, type of surface and so on. This means a precise definition of the user and the action. Quite difficult in this case because a typical sports hall is used by people of different ages, different training levels involved in a variety of different sports activities. In level 2 we measured force, angles, velocities and other biomechanical parameters. In level 3 we studied the effect on a players performance (for example measuring the effect on jump height or running speed), and their general opinion about the surface using different surveys. Then we measured the friction coefficient and shock absorbing properties of a representative sample of indoor sport surfaces according to the existing standards, including other properties, such as surface roughness or materials employed. (Durá *et al.* 1999a, 1999b),

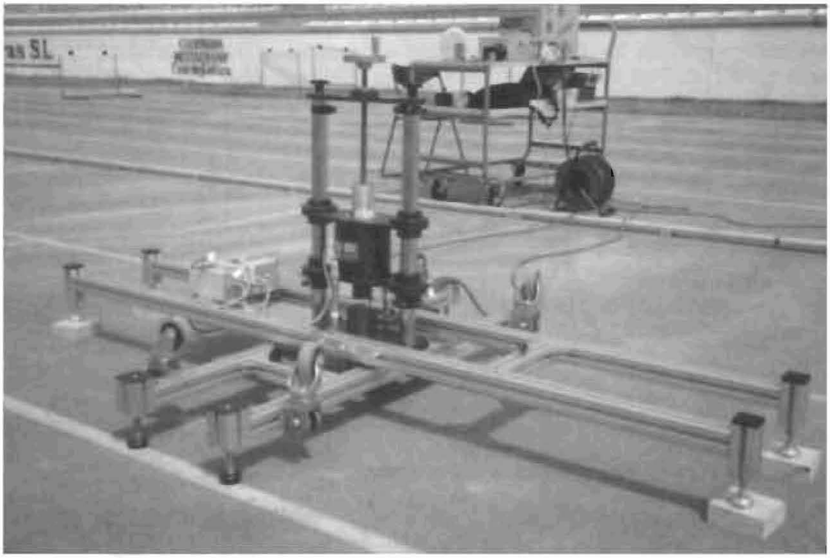

Figure 2. Force Reduction and Deformation tests over an athletic track.

Five samples which covered the existing range of different sports surfaces were selected for friction and another five for shock absorption. The biomechanical study of friction involved a turning movement. The movement commences from a crouched position similar to the start of a 100 m sprint, turns on the first step, with the right foot, to run back in the opposite direction. The subjects were allowed to repeat this action as many times as necessary to adapt themselves comfortably to surface conditions, the objective here being to detect the subjects adaptation to surface factors. Surface samples were fixed onto a force platform DINASCAN-IBV® to measure the force during the stationary phase. Motion analysis was carried out the lower limb was divided into four segments the three joints were defined as the hip, knee and ankle. Three markers were fixed onto each segment; 3-D movement analysis using KINESCAN-IBV® with three video cameras (50 Hz) captured every movement. The hip joint data was eventually discarded from the study since the subjects placed their right arm in front of the marker during almost all of the turning motion (Figure 3). Different parameters were obtained, and with each of these parameters a multifactor analysis of variance of repeated measurements was performed. Subject and surface were considered as factors. A multiple range test of Least Squares Differences (LSD) at 95% was used for *post hoc* analysis to determine which surfaces produced significant differences. The shock absorption study involved a simple vertical jump. (Figure 4) from 42 cm. above the surface. Subjects were asked to jump as high as possible immediately on contact with the surface, keeping their arms crossed over their chest. With the arms in this position the variability of movement is restricted, arm movement could influence height to a greater or lesser extent through movement synchronisation. Before measurements were taken the subjects performed several practice jumps in order to adapt their movements to the surface. The movement was repeated 5 times on each surface. There were 25 repetitions (5 times per person) on each surface. The test subjects wore the same sports shoes, the objective here was to identify the effect of the surface. If the shoes had been different, variability would have increased and perhaps the surface effect would have been unclear. Two extensometric accelerometers were attached to the subjects: one on the lower limb and another to the forehead. The proximal anterior part of the tibia, 3-4 cm under the interior tibial tuberosity was chosen for the lower limb placement. A contact sensor was placed inside the shoe sole to measure both, contact time on the surface and in the air.

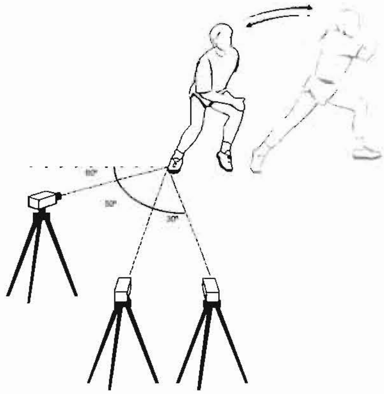

Figure 3. Camera position during the turning movement.

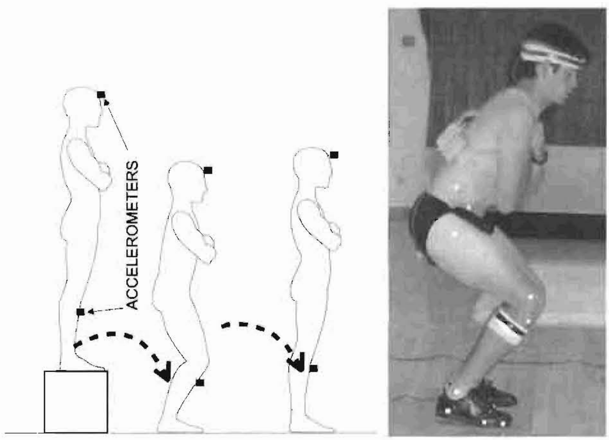

Figure 4. Jumping movement and accelerometer position.

These times were used as a measurement of performance. The signals from the accelerometers and shoe sensor were acquired with a personal computer with an A/D board. The sample frequency was 6000Hz (2000Hz per channel). Eight reflective markers were attached to define four segments (two for each segment) and the movements were recorded in a KINESCAN-IBV® video system at 50 Hz with one camera. A 2D movement analysis was done, and the flexo-extension angles of the hip, knee and ankle were calculated. The decision to do only a 2D analysis was based on the opinion that with the jump movement the flexo-extension is the most relevant and that the angles on other planes are not so important (Sussman 1988). Temporal and kinematic parameters were obtained, and with each of these parameters a multifactor analysis of variance of repeated measures was performed. Subject and surface were taken as factors. A multiple range test of Least Squares Differences (LSD) at 95% was used for *post hoc* analysis to determine which surfaces gave significant differences. The parameter measuring performance in this case was time. In this case, the effect in the users (level 3) was measured using the opinion surveys and the defined performance parameters. In the case of friction (Durá 1999c) the relationship between the friction standard test and survey opinion showed that only 20-25% of user opinion is explained by the test (D-Sommer). The reason could be a defective test or that a single test is unable to evaluate the influence of different shoes, people or sporting activities. Another important result was that the friction range considered as adequate by participants was different from the existing standards. People considered 0.4 low limit to be an acceptable limit, whereas the standard is 0.5. Even more people were satisfied with the lowest values of the accepted range (0.4 to 0.5) than with the highest values (0.6 to 0.7). Using laboratory tests showed that that the performance parameter was uninfluential: i.e. the duration of the turn. Until now we have shown the results of levels 1 and 3 but not level 2, where biomechanical methodology is used i.e. force platforms, cinematography, etc. Then how do we explain why people prefer less friction or why it is necessary to change the limits of low friction. The actual standard says 0.5 to 0.7 and people are satisfied within these limits, perhaps it might be too risky to reduce it to 0.4. Here, perhaps lies the importance of biomechanical research in this case: if we knew why things happen we would be able to with present stronger arguments in favour of change. In this case the biomechanical study showed that two phases formed part of the turning movement, first a braking phase and then a lift off or flying phase. These phases were separated by a minimum of vertical force (Figure 5).

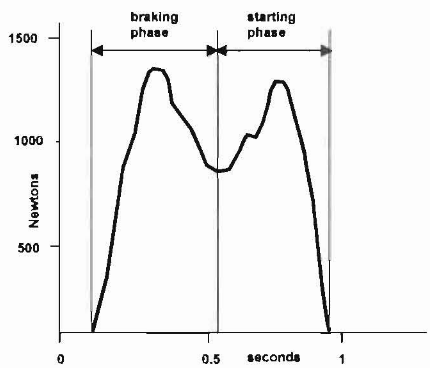

Figure 5. Typical vertical force in the turning movement.

The differences in friction coefficient between surfaces were lower in the tests with people (0.3 between the surface with the lowest friction and the one with the highest friction) than with standard method (0.5). This could be explained by some movement adaptation or modification. The adaptation appears at different moments taken at each movement of the two phases. When the friction force is higher people spend more time braking and less time for starting, this produces the same effect on the mechanical impulses for each phase. In this way, people use the extra time for braking for more knee flexion. This could be interpreted as a protective mechanism. People try to maintain forces and torques within acceptable limits; when the friction force is higher, the torque increases, but this effect is reduced by people using more time for braking and with more knee flexion. For those who participated in this study, the upper limit of acceptable torque was around 30-40 Nm, and this value coincides with the recommendation of Valiant (Valiant, 1990). Considering that the time taken for the turn is a parameter that measures the performance of the movement, and that although this parameter is hardly affected by the different surfaces there is still a compensatory element between the two movement phases. Consequently it is recommended that the surface has a low coefficient of friction, around 0.4 as measured with the standard method. As a result of this biomechanical research the friction standard limits were changed in Spain and there is more research to improve friction test devices. Shock absorption opinion surveys results were similar to those on friction, only 20-25% of the user's opinion is explained by the standard test. People seemed to be happy with an enormous range of the force reduction parameter, even with 10%. According to the standards 10% is extremely low. Once again different explanations exist; maybe the test is bad, or the use of shock absorbent shoes supplement the surface, or people are very accustomed to playing on hard surfaces in Spain. The laboratory tests using biomechanical methodology provided some information to

perhaps, explain the reasons. Different shock absorbency levels create changes in joint flexion to maintain impacts (accelerations) at acceptable levels. The athlete tries to adapt his or her movements to keep protection (impact levels) and performance (jump height) on surfaces with different shock absorbing properties. This adaptation is visible in the changes of flexion angles of the knee, hip and ankle. When the surface is more rigid, knee flexion is higher to maintain impacts (accelerations) at acceptable levels. As the objective of the movement studied was to jump as high as possible, we concluded that modifications in knee angles caused changes in the other joints (ankle and hip) to maximise the jump height. This tendency changes, however when shock absorbency is very high (more than 70%), and high shock absorbing surfaces suffer greater deformations for longer.
We have established that:

- People adapt their movement to surface properties, mainly changing joint flexion angles, and that the performance parameters were different depending on the surface.
- The standard test does not measure the energy restitution parameter. For this reason surfaces with equal force reduction may influence sportsmen differently. (Durá *et al.*, 2002)

As result of this research the Spanish standard recommends higher force reduction for materials with higher energy restitution, for example wood area-elastic surfaces, and less force reduction for both PVC or rubber surfaces.

SHOES EXAMPLES: Another example of this methodology is provided by the tests protocols used by IBV to check the biomechanical and ergonomic quality of shoes. In this case the aim was to define simple tests that measured shoe properties (level 1) related to comfort: friction tests, flexion tests, comfort tests, shock absorption tests, etc. To define the tests we needed to measure how people walk (level 2) in order to define normal flexion angles, forces, etc. And to relate the results to shoe tests with people´s opinion about comfort (level 3) in order to define the characteristics that a shoe must have to be considered good. For example, our research into shock absorbing materials for shoes. We needed to define a test method that would give information about the different parameters that influence comfort and the consumer´s opinion. It was necessary therefore to test a variety of shoes on different people to determine a typical force signal. The tests were conducted on a DINASCAN force platform. The defined test (García *et al.*, 1994) simulates the vertical force of the heel impact measured by our force platform DINASCAN, the parameters of which are dynamic rigidity and loss tangent. The test consists of eight consecutive impacts on material samples. These impacts are described in Figure 6:

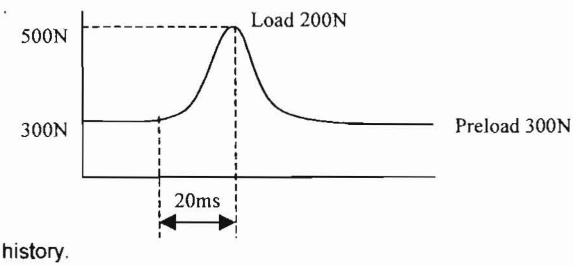

Figure 6. Test load history.

The preload, load and impact slope parameters have been defined to enable a controlled force test with a dynamic testing machine, they have a frequency content of over 35Hz. As a result of this work, IBV is now able of certify the biomechanical and ergonomic quality of a shoe with standard tests. This even includes "quality brands" which are already on the market and being used by shoe companies. More information about this brand can be found on our web page www.ibv.org. And finally, one more example that shows the value of another typical biomechanical device, the pressure insoles. In this case the aim is to obtain design criteria about the main parameters that influence the anatomical elements used in footbeds for the general population. Level 1 is the dimension of the different elements that may appear in footbeds. The selected parameters are shown in the following figure 8.

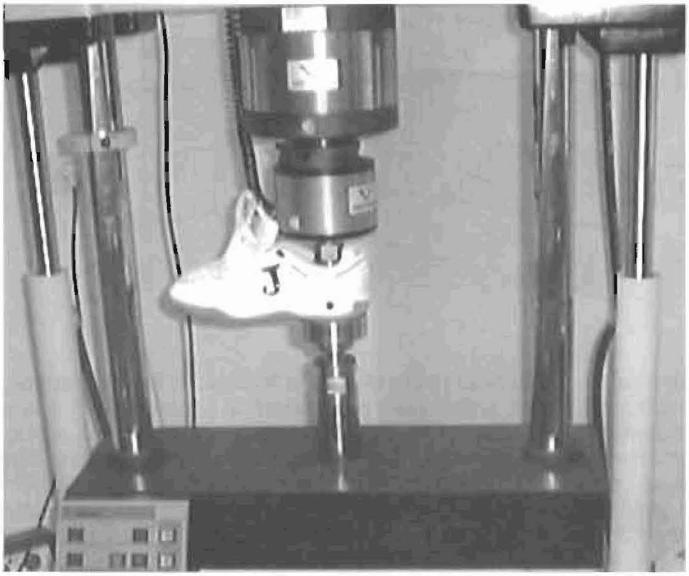

Figure 7. Impact test.

Figure 8. Footbed parameters.

Level 2 relates to the pressures produced into the footbed. Level 3 relates to the comfort or discomfort experienced by the consumer. To study plantar pressure distribution, "Biofoot®" IBV's pressure insoles were used. They consist of a flexible insole with up to 64 piezoelectric ceramic pieces distributed to reflect foot physiology in such a way that there is a greater density of sensors under bony areas. Five healthy male subjects carried out six valid trials, testing each footbed prototype in random order. The statistical processing of the data obtained from the Biofoot® was analysed by some IBV software called BIOTRAT. The development of this software was based on the analysis approach expounded by Shorten (1999). This programme is based on the processing of the data provided by the ceramics through an interpolated grid. Every cell of the insole calculates the mean of several strides from one or more subjects for a particular prototype. An ANOVA study was carried out to determine any significant differences in mean pressure between the conditions studied on any cell within the grid ($p<0.05$). The picture obtained represents the statistically significant differences according to a colour scale. The next, figure 9, shows the BIOFOOT (left) and one example of the statistically significant differences between footbeds with and without a toe bar. The software BIOTRAT developed for the statistical analysis of the data from BIOFOOT® and based on the Shorten paper (1999) represents a great advance for the study of anatomical elements; it is now possible to display exactly the statistically significant differences of any cell anywhere on sole. Therefore, it has been possible to detect effects regarding the height and position of the metatarsal support or even the toe bar, both previously unknown factors (Bataller *et al* 2001).

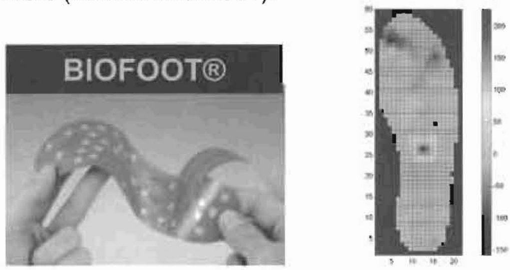

Figure 9.

CONCLUSION: The biomechanical research that is focused in the description of movement patterns, kinematics or other physiological parameters is important, but it is not enough to obtain knowledge applicable at an industrial level. The described methodology used in the Institute of Biomechanics of Valencia for product assessment has been conceived to sum up different areas of research (biomechanics, mechanics, epidemiology and comfort). These different areas yield complimentary information which is relevant of the sports activity. This methodology uses 3 factor levels that are classified according to their place in a hypothetical cause-effect chain. In this manner relevant information could be obtained in order to obtain design parameters for products or for developing new standard tests.

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