EQUIPMENT DESIGN AND TESTING

Hans **J.Gros**
Institut fur Sportwissenschaft, Universitat Stuttgart, Stuttgart, Germany

The paper attempts to summarise goals of equipment design. The interdependencies are described. The development of landing mats for gymnastics serves as example for a typical evolutionary process. Different methods and approaches used to tackle complex problems are discussed for a fictitious example. Potential modifications of vaulting poles and their effect on technique and performance are considered.

KEY **WORDS:** equipment design, landing mats, methodology.

INTRODUCTION: Movement implies interaction between the moving body, in our case the human engaged in sports activity, and the outside world. Interaction can occur between the athlete and team members, opponents, surfaces, water or air and sports equipment or implements. This paper focuses on the design and testing of sports equipment.

'Interaction' implies that the athlete's technique and performance as well as the load on the active and passive structures depend on the type of equipment used. At the same time the athlete chooses the equipment best suited for the purpose.

Safety Considerations: For injury prevention safety considerations play an important role in equipment design. I shall discuss this aspect using the example of landing surface design for gymnastics later in this paper. It is a truism that 'only a healthy athlete is a good athlete'. To succeed, exceptional talent has to balance a well planned long term training process with adequate numbers of repetitions, series and intensities. Amongst factors like genetic predisposition, and medical care the equipment as interface between athlete and environment is of paramount importance.

Performance: Performance is one of the prime motivators in sports. We observe a professionalisation of training methods, duration, and intensity. This is a consequence of societal demands and economic incentives. The results of this process include increased performances and a growing density of the top performances. Hence it is obvious that the interest in equipment is not new. What has changed are the approaches and the time and effort spent. Athletes have always tried to take advantage of the potential improvement made possible by new materials.

The FES (Institute for Research and Development of Sports Equipment) in Berlin, Germany, was founded almost 40 years ago and has been an extremely successful developer and supplier of high tech sports equipment. The basic philosophy is a cooperation of engineers, sports scientists and medical staff. One key to successful equipment design is the corporate planning and evaluation. Input and feed back is sought from coaches and athletes throughout the developmental process. The combination of solid science and the practitioners 'feel' in an iterative process is a systemic approach with focus on the interaction between athlete, implement / equipment, and environment. Customising equipment to individual anthropometry and physical condition is necessary on the top performance level. Technique is adapted where necessary. The gains in performance made possible by these developments often surpass the potential increase due to improved or augmented training.

The rules defined by sports governing bodies and their technical committees frequently had to be adapted to account for evolution. Consider the javelin. Improved materials and most important improved aerodynamics enabled athletes to throw distances of over 100 m that were a security risk in any stadium. The 'old' javelin was optimised through many wind tunnel tests and field experiments (Terauds, 1985) such that the centre of pressure (CP) moved in front and behind the centre of mass (CM) as a function of the angle of attack. This aerodynamic feature made the javelin sail and land flat. The IAAF chose to modify the rules governing the javelin design such that the CP always remains behind the CM. This creates a pitching moment that tends to bring the tip down. This is an example where equipment had to be made 'worse' to comply with the rules. The rule change brought the desired effect: the throwing distances were reduced by about 20%. At the same time athletes with a different anthropometry and strength profile succeed since they are obviously better adapted to the changed implement.

Sporting Goods Industry: The sporting goods industry is a third motor for equipment design. The goal is to use performance and safety aspects and combine them with new trends to create markets for the products. Since the true innovation rate is usually slower than market induced need for novelties we often observe the emergence of gimmicks.

Kreighbaum (1996) stated: "High-tech buzzwords fill advertisements. Vibration-free, ceramic, boron, graphite micro-mid, asteroceramic, energy wave, flexlite, motion control, vibrasorb, stabilized flight, hydroflow, anatomical cradle, and adjustable flex are but a few of the concepts and space-age materials that entice the buyer."

Figure 1 attempts to visualise the field of equipment design in a coordinate system. Let performance, safety / injury prevention and industry / marketing be the X, Y and Z axis of a coordinate system. Vector one represents a strictly performance oriented development which accepts the increased risk of injury. Vector two depicts the case where injury prevention is improved but the piece of equipment is not likely to succeed since it is not fashionable and detrimental to performance. Vector three is the 'harmless gimmick'.

This continuum is influenced by factors such as societal norms and boundary conditions defined by rules and regulations. Most important it is modulated by the user's needs and demands. "Equipment must be comfortable to use, aid in successful performance, be affordable as well as fit the user's size, shape, strength and ability" (Kreighbaum, 1996).

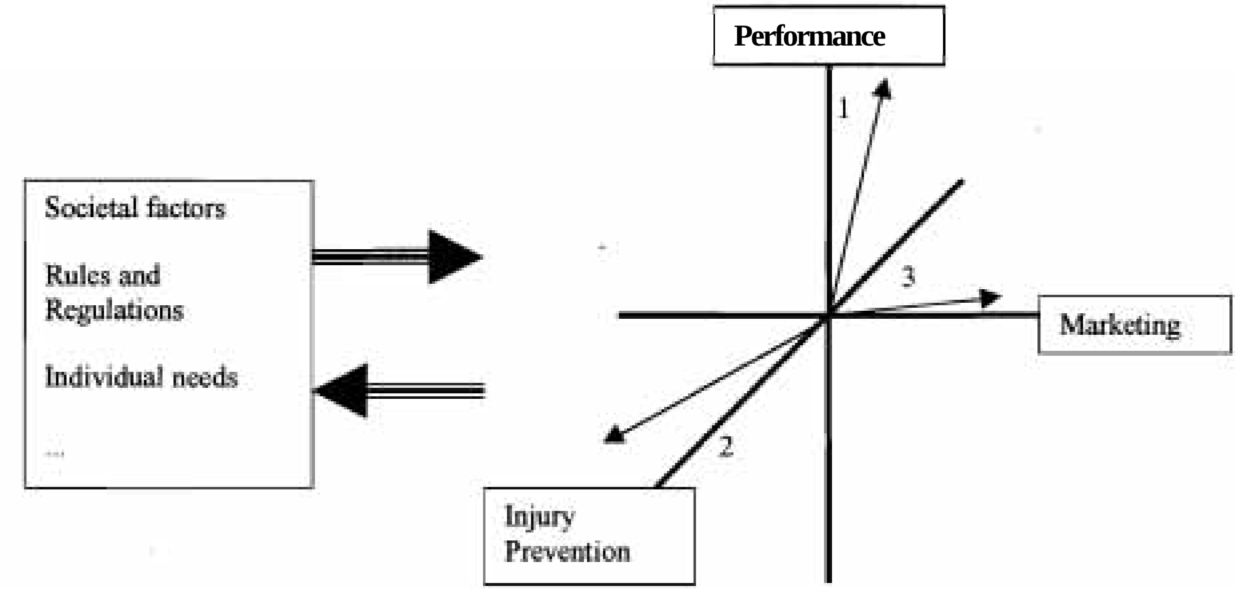

Figure 1 - **Equipment design between the goals of performance enhancement, marketing interest and injury prevention.**

It is necessary to understand the entire system and consider possible synergetic effects if one aspires to successfully design equipment for sports. The 'good designer' is usually a team of experts that brings together knowledge of biomechanics, anthetrics and aesthetics. Boundary conditions imposed by societal agencies and sports governing bodies are considered. The goals must be clearly defined. The target group or individual have to be known in terms of anthropometry, biomechanics and physiological profile. I will use the development of landing mats as an example.

THE DEVELOPMENT OF **LANDING SURFACES** IN GYMNASTICS: Competitive gymnasts and their coaches have in the past and continue to develop elements of increasing difficulty. This is made possible by highly professional training and social environment as well as improved equipment. Training and execution of complex skills (like triple twisting somersaults) require increased flight times. The need to generate large impulses in short time periods and the subsequent need to absorb energy in the landing phase potentially leads to acute injury or chronic degenerative processes. There are several ways to cope with this vicious circle:

1. Limit the difficulty of stunts. This could be forced by not rewarding the risk and novelty aspects in the Code de Pointage. The somersault in figure skating is an example where this was done. However this potentially leads to stagnation in the development of the sport. The spectator does not want injuries (see the discussion on long term damage in female gymnasts) but still innovation is needed to keep the sport attractive.
2. Allow for load reducing landing techniques. This option was discussed in the early 1980's (Gohner, 1981). Research showed that the loads could be substantially reduced for example in vaulting if one allowed for a forward role rather than 'sticking' the landing. Similar evidence was reported by Brown (1995). The 'roll out' landing would have to be pushed by abolition of the point deduction for non standard landings. However this was not done for a very good reason: allowing for an 'arbitrary landing' could be counter productive since gymnasts would take even higher risks in their aerial stunts thereby increasing the injury potential due to bad landing technique.
3. The gymnastics world (i.e. the gymnasts, coaches, equipment manufacturers and the FIG) decided to tackle the problem from the equipment side. The rationale was simple: To reduce loads incurred in landings and potential injuries or long term bionegative adaptation we provide better landing surfaces. If we say 'better', we need to operationalize the improvement. This can be done through subjective evaluation or measurements. The first quantification of the mechanical behaviour of mats was attempted by dropping a 10 kg mass from a height of 40 cm. The height of rebound was determined and used as indication of energy absorption. A low rebound was considered 'better'. However this simple test device has serious shortcomings. When a mat is compressed beyond it's elastic range it 'bottoms out'. This results in a dramatic increase in peak force. The rate of force development and the maximum force are decisive factors for the load on the system.

The FIG initiated a research project to find a more reliable and repeatable testing procedure for landing mats. Schweizer (1985) designed a test system where a solid mass instrumented with an accelerometer was dropped onto the mat. The signal was integrated twice to yield deflection data. The force - deflection curves disclose the 'bottoming out' of test samples. This is depicted in Figure **2**.

The test system designed by Schweizer (1985) yields information on three basic parameters: The compression, the rebound height and the peak force. Schweizer used existing mats to define boundary values. His test is still used today to standardize mats used in official competition.

To obtain the FIG seal of approval the maximum peak force (FOmax) and rebound height are limited. The permissible compression is also limited. The rationale for this is that foot fixation occurs when compression is too large. From 1985 to 1998 the height of the mats was increased from 12 to 20 cm for most apparatus. Table 1 summarises the norm values.

Table **1** FIG Norm Values for Different Height Mats

	12 cm	15 cm	20 cm
Compression	< 105 mm	< 105 mm	< 110 mm
Rebound	< 150 mm	< 100 mm	< 120 mm
Maximum Force (FOmax)	< 4500 N	< 4000 N	< 3650 N

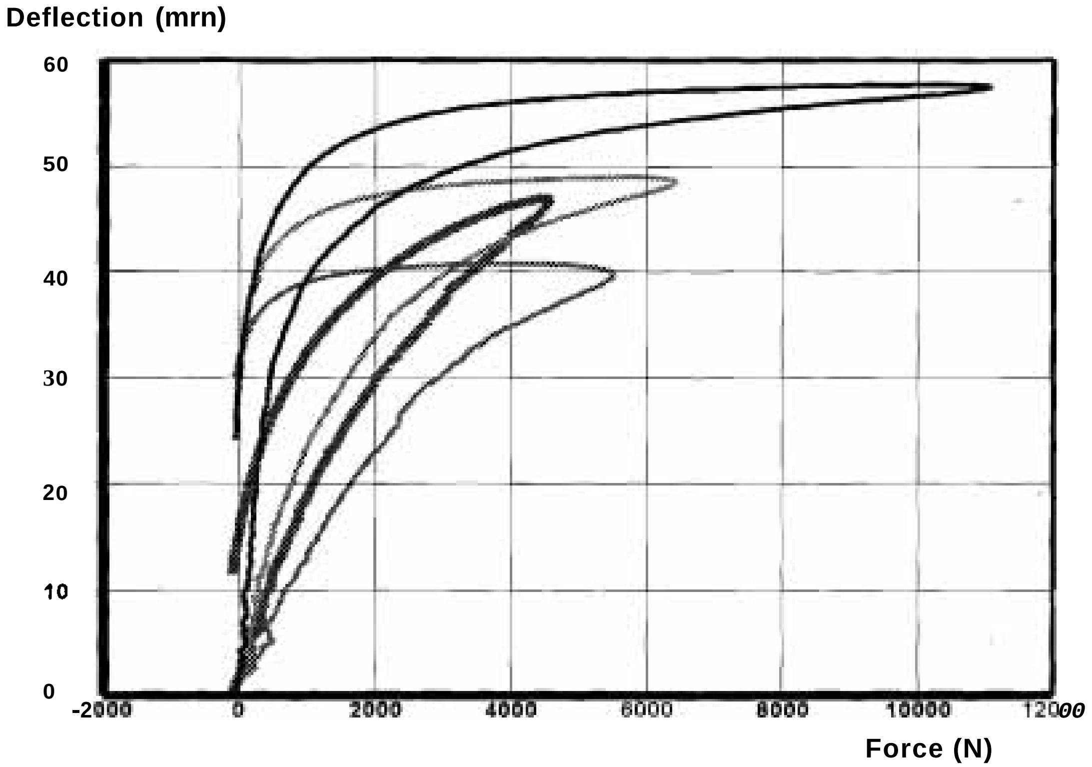

Figure 2 - **Force deflection curves for mats showing a mat with increasing force (FOmax) when no further compression is possible.**

Gros and Leikov (1990; 1994b) criticised the FIG norm. They argued that a large compression is necessary to decrease the decelerating forces and that foot fixation can be avoided by having a surface elastic rather than a point elastic top layer. In light of the fact that good 15 cm mats easily fulfilled the 20 cm norms they demanded stricter norms, advocated to permit larger compression of the thick mats and asked the question whether the basic concept of landing mats is correct.

As is often the case, gymnasts and coaches went ahead and changed the mats themselves to suit their needs. Previously, thin hard floor mats on top of soft mats were used in training. Then, around 1993, 'ultra soft' mats on top of landing mats were observed. This combination had proven to work for kids who were simply too light to effectively use the landing mats. It was then adopted by older gymnasts since they subjectively noted vastly reduced loads on their bodies. The German Gymnastics Federation and then the FIG followed the trend and authorised the use of complementary soft mats for dismounts and landings. For the men soft mats were allowed for high bar dismounts and vault landings in 1995. Female gymnasts are allowed soft mats without point deduction since 1997.

Bruggemann, Arampatzis, Alp, & Janshen (1993; 1998) have researched gymnastics landings. Their work shows that the FIG norm and the associated testing procedure may be a useful tool to standardise mats of different manufacturers and thus ensure comparable conditions for international competition. However, the mechanical drop test is not suited to compare and improve mats or design new landing systems. The reason is very simple: the stiff one segment mechanical system impacting with pre defined energy does not adequately represent the biomechanical system. Also, the interaction between the active system that absorbs energy through eccentric contraction of the extensors and the passive system 'landing mat' cannot be represented by this simplistic mechanical model.

An increase of the thickness of the landing mats is not the answer to the problem how to reduce load on the gymnast: good 15 cm mats easily fulfil the norms for 20 cm mats (Gros and Leikov, 1994). Only a thorough understanding of the landing system and the interaction between gymnast and mat may improve the situation. Briiggemann, Arampatzis, Alp, & Janshen (1998) present an orderly approach to the optimisation of landing mats. The approach is the culmination of several years of research. It exemplifies how solid science can be applied. In the following section of this paper I shall try to summarise the research questions asked and report some of the results.

In a first step, a biomechanical profile of gymnasts[1] landings in energy terms was determined in competition landings. The highest kinetic energies at touch down of 1050 - 2050 J (high bar), and 1100 to 1800 J (vault) are reported for males. 800 - 1150 J (vault and uneven bars) were measured for female gymnasts.

The second problem is the estimation of the energy absorbing capacity of the leg extensors. Based on knowledge of the negative dynamic work done in the eccentric phase, conclusions on the energy absorption requirements of the passive system (landing mats) and the mechanical properties of such mats can be drawn.

In a third step the influence of the landing mat on the behaviour of the of the leg and hip extensors was researched. The initial contact phase lasts about 100 ms. The mat reaches it's maximum energy absorption (700 J) after 50 to 60 ms. The gymnast absorbs about 300 J (roughly 5 J/kg BM). Due to the electro-mechanical delay the landing induced increase in EMG activity cannot account for the stiffness modulation of the active system. Initial stiffness is regulated through pre-innervation.

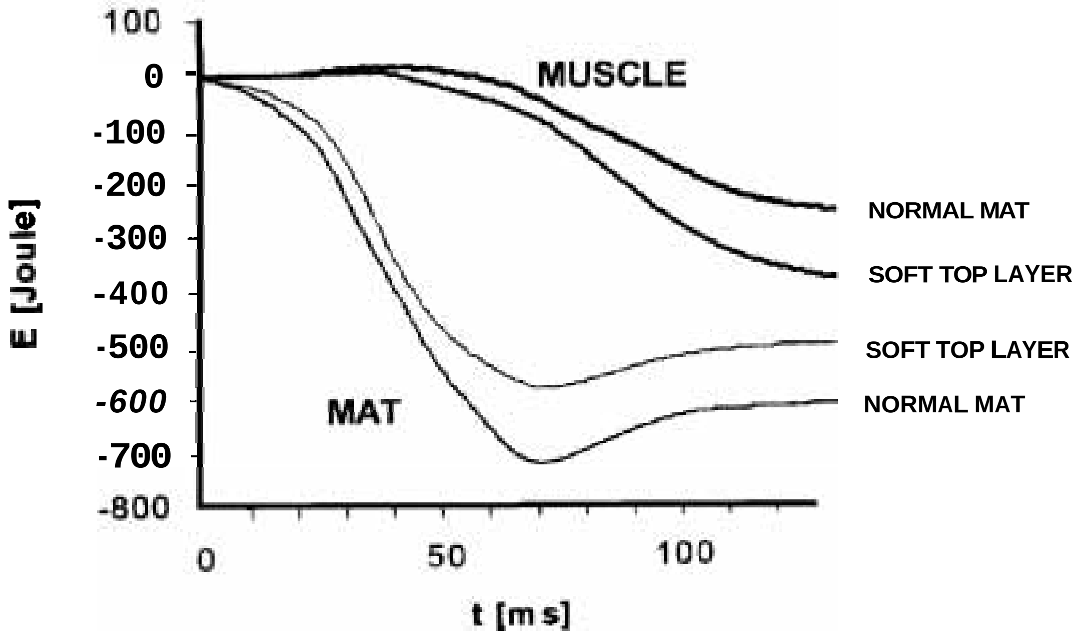

Figure 3 - Energy absorption through the mat and eccentric muscular work in the initial 100 ms after landing (adapted from Brüggemann et al 1998)

The comparison of a traditional mat and an experimental mat with 5 cm thick soft top layer showed that the energy absorption capacity of the muscle increased considerably as is shown in Figure 3.

This leads to the conclusion that conventional mats are too stiff for the initial collision with the biological system. The pressure between the FIG norm test mass as well as the plantar pressure below the feet was measured on FIG certified conventional mats. The data show that neither the maximum pressure nor the rate of pressure development correspond. Thus the FIG test cannot be used to optimise mats.

In a fifth step a standard 20 cm mat (NORM) was compared to an experimental mat (EXP) with 16 cm homogenous foam plus denser top layer and plastic cover. Landing energies of 550 J produced lowest maximum Forces on NORM. However, an increase of the initial energy to 850 J reversed this tendency. Furthermore, the rate of force development is much lower in EXP. The experimental mat with it's 'soft' characteristic matches the requirements of the landing biomechanical system much better than the mats produced according to the current FIG norms. If the stiffness of the mat in the initial contact phase is greater than the stiffness of the landing gymnast (≈ 70 - 80 kN/m) the interdependence between the active and passive elements in landing is neglected. Design criteria for improved mats include a low stiffness of the top layer and progressively softer layers in the middle and bottom parts. Such mats would work for competitive gymnastics as well as the general school and club training.

Further research incorporating specialists from the fields of modelling, material science, biomechanics, engineering, and orthopaedics working in cooperation with manufacturers, gymnasts, coaches and sports governing bodies is currently under way (BISP project 'Landing mats').

A FICTITIOUS RESEARCH QUESTION: The two most important things in applied research are: Have a good question and choose the right tool to answer it. This sounds trivial but is often neglected. The inadequate method is likely to produce non-optimal results. We are likely to get caught in the confinement of our own reductionism and the methodological inadequacies. In the following section of this paper I shall attempt to compare different approaches to solve a fictitious research problem.

A biomechanist is approached by a company. The company produces fins for divers and asks the simple question: "What makes a good fin?"

The first step is to define what is a good fin, what kind of performance do we expect from the equipment. One answer might be a catalogue of criteria. For the purpose of this paper let's assume the criteria are:

C1 = Maximize propulsion

C2 = Minimize energy cost for a given propulsive force.

Propulsion can be quantified in terms of propulsive force generated or in terms of velocity attained.

A second step is the definition of the population (e.g. professional divers vs. recreational snorkelers)

We now have a range of instruments and methods to approach this complex problem.

I will describe the methods and discuss advantages, limitations and pitfalls.

Approach 1 is a classic empiric approach. We look at the system and measure whatever is measurable. We know that singular methods do not tell the whole story: 3D kinematics, direct measurements of resulting propulsive force, physiological parameters such as VO_2, HR, lactate...and electromyography all give us fascinating facets of the total movement. Each method by itself produces rather meaningless results. The combination of results produced by several methods allows for a much better understanding. The empiric approach requires a problem adequate combination of methods.

We then choose X Subjects and Y fins and Z Criteria. If we look at a specific fin and a specific criterion we have to bear in mind that the human body is not a motor with known characteristics. There is interdependence between the kinematics of the body and the resulting propulsion and energy cost. Thus we will get the result that the fin that best fits the kinematics of a subject is the best fin. This result cannot be generalised. Since the tests are usually too short to fully accommodate to the equipment we neglect the 'learning adaptation' and the interaction between fin Y and subject X. Statistics does not solve this problem. We end up with 'general recommendations' or doing highly individualised fitting of the piece of equipment. Latter is only feasible in equipment design for high performance sport.

Our research identifies the fin of the ones researched which best fits the subjects of the study. We have no way of knowing whether this fin is really optimal, for what subjects it is best, how well the subject can adapt to the fin and what the optimal fin should look like. At best we describe realities and select the 'least lousy' fin for the largest possible portion of the population. The fin that best happens to fit our sample will be the 'test winner'. This type of failure to solve the real problem is very common.

Approach 2 is a classic knowledge based mechanical model. The first step is the identification and selection of the relevant variables. We have to model the kinematics and kinetics of the human and we need a model of the fin. Let's assume a three segment leg model with a fin. We need all anthropometric anatomic and muscular information. For example we have to mathematically formulate the net moments produced at the joints. These moments change with muscle force and lever arm which are a function of muscle length, joint angle, angular velocity and other factors. We then need to consider the interdependencies of the joint torques.

Once the equations are derived and the model has been tested we can simulate the behaviour of the system. We selectively change single variables and observe the result on the dependent variable (i.e. our criterion). The changes are defined by the scientist. Some models incorporate optimising algorithms. The literature on this approach is abundant and includes authors such as Hatze (1998), Spagele et al. (1999), Pandy et al. (1990).

The problem for our research question is the need for an explicit mathematical formulation of the systems of tremendous complexity. The hydrodynamics of the leg and fin alone are almost impossible to incorporate into a model that fulfills the mappingriterion (Stachowiak, 1973). The transfer from a mechanical model to a biomechanical system is extremely difficult.

Approach 3 uses a neural network and the algorithm of Kohonen (1982). Let us construct a physical model with three segments (thigh, shank, and foot) plus a given fin. The model is submerged in a water tank and has (for simplicity) rotational degrees of freedom in the joints (hip, knee and ankle). For this 'robot limb' we define the ranges of motion and the net joint torques for each joint. We use motors to move the segments according to a function defined. As in approach 2 we need the moments that can be generated as a function of angle, angular velocity etc. With this function (Kennlinie) we drive the motors in the joints. The total limb be attached to a force transducer. The output of this transducer serves as feed back for the learning neural network. It is important to note, that no hydrodynamic model is required (as was the case in the knowledge based mechanical model).

The network can now learn to move (i.e. adapt the kinematics) in a way to let's say maximise propulsion or minimise energy cost (operationalised as the sum of current uptake of the motors). The 'leg' would have to be mounted in a water treadmill to optimise velocity.

Approach 4 is based on the concept of an evolutionary algorithm. We define a given kinematic. The algorithm works with random variation of the fin. The result is the model of a fin that best fits the kinematics. The evolutionary algorithm checks and selects the most successful 'survivor'. A frog's webbed extremities are the current status quo of a natural 'evolutionary algorithm' for the task 'survival of the species in water and on land'. For the scientist the problem of the hydrodynamic model of the fin remains but unlike approach 2 the algorithm produces it's own mutability of the variables and needs no explicit representation of the biomechanical system.

Approaches 3 and 4 are not knowledge based. They are implicit representations. The result works but we often don't know how and why the solution found functions. The problem of how to transfer the results to the biomechanical system remains to be discussed and solved.

THOUGHTS ON POTENTIAL DEVELOPMENT OF VAULTING POLES: In the final section of this paper I will toss around ideas of potential future developments of vaulting poles. My starting point is a glance at pole development in the past and some energy considerations. The history of pole vaulting is an excellent example of how performance increased as a result of improved materials and equipment. Also the interdependencies between the equipment properties, mainly the energy storage as a function of the pole deflection and the resulting necessary technique adaptations have been described. Basically the stiff poles resulted in substantial energy dissipation during takeoff. This limited grip height for a given velocity and plant angle. Top vaulters can clear heights approximately 1 m above grip height. Thus performance is limited by grip height. A fiberglass pole deflects under the axial load. This deflection causes a reduction of the chord length by about 1,4 m, a smooth transition onto the pole and thus allows for increased grip heights. Figure **4** shows the resulting path of the top hand.

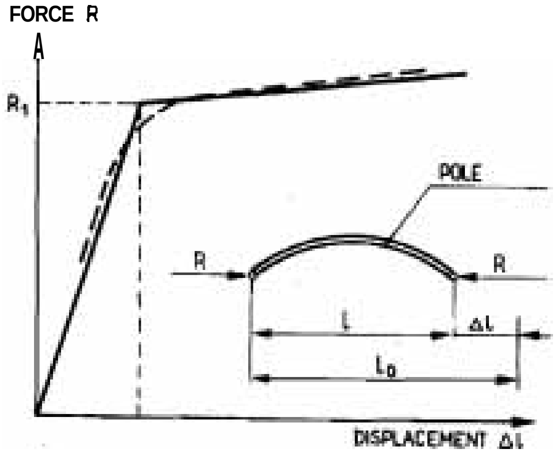

Figure 4 - Schematic of path of top hand for a vault with a stiff pole (A) and a flexible pole (B)

The bent pole stores energy and returns it to the vaulter in the straightening phase. The integral under the load - deflection curve is the energy stored.

The first question is: could the pole be designed in such a way that it allows for larger deflections? Vernon (1974) asked this question and designed a 'curved pole'. The use of a soft pole does not work since it will not straighten. Fidelius et al. (1978) simulated different stiffness poles for given initial conditions on an analog computer. Their results are depicted in Figure 5.

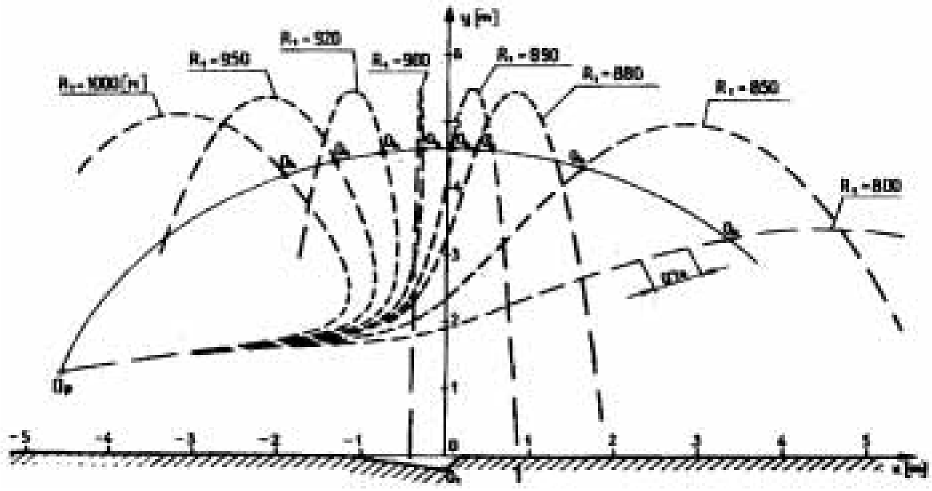

Figure 5 - Effects of varying pole stiffness in a computer model (Fidelius, K. et al. 1978)

Let us now consider a hypothetical pole with a modified load - deflection curve. If a pole had the behaviour of a tendon, i.e. a shallow toe region preceding the linear increase, then this pole should have larger deflection which would in turn allow for increased grip heights. The toe region in the stress - strain curve of the biological material is caused by an alignment of collagen fibres. Could a pole be built with a 'tendon like' behaviour? Assuming that this 'joint venture with mother nature' works: can this pole be vaulted? This question could be tackled with a computer model and simulation. Finally, how would the vaulting technique have to be adapted to the potential and properties of the pole?

CONCLUSIONS:

1. Successful equipment design requires a multi- or interdisciplinary approach.
2. The goals need to be clearly defined on the basis of a sound understanding of the mechanics and biomechanics of the system.
3. Interdependencies and synergetic effects between athlete and equipment must be understood.
4. If we deal with top athletes all measures need to be customized to the athlete's anthropometry and physiological profile.
5. One does not have to know the answer but one should know and ask the right question.
6. Imagination is more important than knowledge (A. Einstein).
7. Innovation becomes unlikely if the self imposed correctness and scientific discipline result in the straight jacket of 'reductionism' or as Nietsche put it: " You need chaos to give birth to a dancing star".

REFERENCES:

Alp, A., & Brüggemann, G. P. (1993). Biomechanische Analyse von Landematten im Gerattumen. In Brügegmann, G. P. (Ed.) *Biomechanics in Gymnastics.* Cologne.

Brown, E.W., Witten, W.A., Espinoza, D.M., Witten, C.X., Wilson, D.J., Wisner, D.M., Weise, M., & Learman, J. (1995). Attenuation of ground reaction forces in dismounts from the balance beam. In Bauer, A. (Ed.).*Proceedings of the XIII International Symposium on Biomechanics in Sports,* Thunder Bay, Canada.

Bruggemann, G. P., Arampatzis, A., Alp, Y., & Janshen, L. (1998). Optimierung von Niedersprungmatten fur das Kunstturnen. Research Report for the Federal Institute of Sport Science (BISP), Cologne, Germany.

Fidelius, K., Morawski, J., & Wiklik, K. (1978). Analog simulation in sports. In Marhold, G. (Ed.) *Biomechanische Untersuchungsmethoden im Sport. Internationales Symposium,* Karl Marx - Stadt.

Gohner, U. (Ed.).(1982). Verletzungsrisiken und Belastungen im Kunstturnen. Schorndorf: Hofmann.

Gros, H. J., & Leikov, H. (1994). Safety considerations for gymnastics landing mats. In Barabas, A., & Fabian, G. (Eds.). *Proceedings of the XII International Symposium on Biomechanics in Sports,* Budapest, Hungary.

Gros, H. J., & Leikov, H. (1994 b). Niedersprungmatten - von Entwicklung und Normierung zu Einsatz in Training und Wettkampf. *Leistungssport,* 6, 25 - 28.

Hatze, H. (1998). Biomechanics of sports - selected examples of successful applications and future perspectives. In Riehle, H., & Vieten, M. (Eds.). *Proceedings of the XVI International Symposium of Biomechanics in Sports.* Konstanz, Germany.

Kohonen, T. (1982). Self-organized formation of topologically correct feature maps. In *Biological Cybernetics* 43, 1148 - 1151.

Kreighbaum, E. F., & Smith, M. A. (1996). *Sports and Fitness equipment design.* Champaign: Human Kinetics

Pandy, M. G., Zajac, F. E., Sim, E., & Levine, W. S. (1990). An optimal control model for maximum-height human jumping. *Journal of Biomechanics,* 23, 1185 - 1198.

Schweizer, L. (1985). Prüfverfahren fur Niedersprungmatten, Bodentumflachen und Sprungbretter. Freiburg.

Spagele, T., Kistner, A., & Gollhofer, A. (1999). A multi-phase optimal control technique for the simulation of a human vertical jump. *Journal of Biomechanics, 32,* 87 - 91.

Stachowiak, H. (1973). Allgemeine Modelltheorie. Wien.

Terauds, J. (1985). Biomechanics of the Javelin Throw. Del Mar: Academic Publishers.

Vernon, J. B. (1974). Curved vaulting pole. *Track and Field Quarterly*, 177 -179.