ON THE POTENTIAL OF VARIOUS APPROACHES IN LOAD ANALYSIS TO REDUCE THE FREQUENCY OF SPORTS INJURIES

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Abstract—The purpose of this paper is to discuss various approaches used in load analysis with special consideration of whether there is some evidence that these approaches have actually contributed to a reduction of sport injuries and whether these approaches have the theoretical potential to reduce the frequency of injuries at all. Two possible approaches are compared.

The 'cause-effect approach' uses the estimation of internal stress. It is proposed that a comparison of the internal stress with the critical stress limits for an anatomical structure of interest may not help to reduce the frequency of injuries for two reasons. Firstly, the estimation of the critical stress limits and the internal stress may have significant errors which inhibit possible conclusions. Secondly, the information provided by the comparison of internal stress and critical stress limits was implicitly available in the injury frequencies and no new knowledge has been added. It is proposed that stresses estimated from model calculations can successfully be used to reduce the frequency of injuries if they are compared (comparison technique) with stresses estimated for comparable situations (e.g. shoes with and without orthotics).

The 'empirical approach' is based on the assumption that the knowledge of the mechanisms of an injury is not a prerequisite for the reduction of the frequency of injuries. The approach establishes statistical correlations between factors related to injuries on one side and specific injuries or groups of injuries on the other side. This approach has frequently been used in the development of sport shoes. It is speculated that studies using an empirical approach have the potential to actually reduce the frequency of injuries.

The conclusive evidence that biomechanical research in load analysis has in fact contributed to a reduction of the frequency of injuries is still missing for both discussed approaches.

INTRODUCTION

Load on the human locomotor system and/or on parts of it can be defined as the sum of the forces and moments acting on the body of interest (Nigg, 1985). Load acting on structures of the human locomotor system during sports activities is one possible stimulus to maintain and/or increase the strength of biological materials such as ligaments, tendons, muscles, bones and articular cartilages. However, if excessive, load may be the reason for micro- or macrodamages of anatomical structures. Several studies suggest that load is excessive in many sports activities. It has been reported that between 27 and 70% of runners or joggers are injured in the period of one year (Clement et al., 1981; Brody, 1982; Jacobs and Berson, 1986; Warren and Jones, 1987; Marti et al., 1988; Bahlsen, 1988) and that between 21 and 52% of tennis players are injured per season (Biener and Caluori, 1977; Nigg and Denoth, 1980). Injuries related to aerobic activities have been reported for 76% of the instructors and 43% of the participants (Francis et al., 1985; Richie et al., 1985). The numbers suggest that there is a problem and that steps should be taken to reduce the frequency of sport injuries.

Various questions may be of interest in the analysis of sport injuries including the anatomical structure damaged (James et al., 1978; Clement et al., 1981), the type of damage (Biener and Caluori, 1977), the external forces acting on the athlete during movements which may lead to an injury (Cavanagh and Laforce, 1980; Frederick et al., 1981), the actual internal forces or stresses acting in an anatomical structure before and possibly during an injury (Zernicke et al., 1977; Zernicke, 1981; Renstrom et al., 1988), the factors influencing external and/or internal forces and stresses (Clarke et al., 1983; Snel et al., 1983; Nigg et al., 1987a; Stacoff et al., 1988), the material properties of the damaged structures and their critical limits (Yamada, 1970; Noyes and Grood, 1976; Shrieve et al., 1988; Stuessi and Faeh, 1988), the factors influencing the material properties and the critical limits (Tipton et al., 1970; Woo et al., 1984; Amiel et al., 1982) and others. However, one of the main goals of research related to sports injuries should be to reduce the frequency of these injuries. Therefore, it seems appropriate to question whether and how much research related to sports injuries in fact has contributed in the past to a reduction of sports injuries. Furthermore, it may be of interest to reflect on whether particular approaches in the analysis of load acting on the human locomotor system have the potential to contribute to a reduction of sport injuries.

The purpose of this paper is to discuss various approaches used in load analysis with special consideration of whether (a) there is some evidence that these approaches have actually contributed to a reduction of injuries, and whether (b) these approaches have the theoretical potential to reduce the frequency of injuries at all.

The discussion in this paper is limited to one specific aspect of load analysis. However, it is suggested that
this aspect is important for research dealing with sport injuries.

GENERAL COMMENTS

Research performed to affect the frequency of one specific injury or a group of injuries may proceed following a general pattern. Firstly, the facts which influence particular injuries are studied. Secondly, attempts are made to understand the connection between these factors and the injuries. Thirdly, attempts are made to influence the relevant factors to reduce the frequency of injuries. Fourthly, evidence is provided to verify that the selected strategies in fact reduce the frequency of injuries.

Ideally, the first and the fourth steps are made by using prospective epidemiological studies. However, different approaches may be used for the second and third steps. One possibility may be a mechanistic 'cause-effect approach', another one an 'empirical approach'. The following paragraphs will concentrate on the explanation of these two approaches and on their actual or possible effect on a reduction of sport injuries.

A 'CAUSE EFFECT APPROACH'

The approach which will be referred to as the 'cause-effect approach' is based upon two mechanistic assumptions which describe the factors and conditions of importance. They can be summarized as follows:

Two factors determine whether a particular anatomical structure is injured because of a stress acting upon it, the critical stress limits of the structure and the stress acting on the structure. A particular anatomical structure is injured if the stress acting on that structure during a specific activity exceeds the critical stress limit of that structure.

In order to contribute to a reduction of the frequency of injuries it could be proposed that research in biomechanics should ideally take a series of steps: (a) it should identify for each particular injury the structure which is endangered or in which the stress limit has been exceeded; (b) it should determine the critical limits of the endangered or damaged anatomical structure; (c) it should determine the stress in the endangered or damaged structure and compare it to the stress limits; (d) it should identify the factors influencing stress in the endangered structures and develop strategies of ensuring that stresses stay below the critical stress limits. The methods used in these steps, and their strengths and weaknesses, will be discussed in the following paragraphs.

(a) Injured structure

The determination of the injured structure may prove to be difficult in some cases. A medical diagnosis does not always allow one to determine the injured anatomical structure. One diagnosis may include different structural damages in one clinical category. The diagnosis 'shin splint', for instance, may include myotendinitis of the tibialis anterior or posterior, interosseus membrane tearing, fatigue fracture of the tibia (Hoerner and Langer, 1986) or may be limited to musculotendinous inflammation of the tibialis posterior and/or anterior at the lower leg (Friedmann, 1986). However, the actual stresses and stress limits in these anatomical structures are different. Most of the stresses will be below, and most likely only one of them will be above, the critical stress limit. Part of the problem can be overcome with increased medical sophistication allowing greater diagnostic accuracy. However, there are still a number of situations where an accurate determination of the damaged structure is not possible. Additionally, referred pain may make the determination of the damaged anatomical structure difficult or even impossible.

The accurate determination of the overloaded anatomical structure is a prerequisite for the successful application of the 'cause-effect approach'. The discussed problems suggest that there are cases where this is not possible and, therefore, this approach may not be applicable.

(b) Critical limits

The determination of the individual critical limits of a particular anatomical structure may be considered an important part in the 'cause-effect approach'. The critical limits set the boundaries in which the stresses must be to avoid damage of the anatomical structures. Mean critical force and/or stress limits have been determined experimentally using cadaveric tissues (Yamada, 1970; Noyes et al., 1974; Trent et al., 1976). Studies on human materials have been preceded and/or complemented by studies on animals. It has been found that the critical limits are influenced by immobilization and remobilization (Woo et al., 1984), age, temperature, skeletal maturity and other factors (Akeson et al., 1986). In vitro studies indicate that the inter- or intra-individual differences might exceed 100% if compared to the minimal values measured (Nipton et al., 1970; Amiel et al., 1982). The probability for significant errors in the estimation of actual critical stress limits in vivo is high.

The accurate determination of the critical limits of the endangered or damaged anatomical structures in vivo is a prerequisite for the successful application of the 'cause-effect approach'. The discussion above indicates that the determination of the critical stress limits with sufficient accuracy is difficult with the currently available methods. This suggests that there may be some problems in the successful application of the 'cause-effect approach'.

(c) Internal stress

Stress is defined as force per unit area. In order to determine internal stress the geometrical dimensions of the anatomical structure of interest and the force acting on it must be known.
One may successfully attempt to determine geometrical dimensions of bone in vivo by using three-dimensional X-ray or NMR techniques with acceptable accuracy. However, there are, for instance, still unanswered questions concerning the size and location of the contact areas between patella and femur in various knee configurations (Hehne, 1983), a variable which is crucial in the stress determination for the patello-femoral joint. Additionally, the determination of geometrical dimensions of ligaments, menisci or tendons for various loading conditions in vivo may prove to be difficult if not impossible. These examples suggest that one of the two components determining the calculation of stress, the area, may be affected with errors which can make the determination of internal stress with sufficient accuracy difficult or impossible.

The methods used to estimate the forces in internal structures of the locomotor system apply often two steps: (a) the determination of the resultant external joint forces and moments, \( F_\text{ext}(t) \) and \( M_\text{ext}(t) \) respectively, and (b) the distribution of \( F_\text{ext}(t) \) and \( M_\text{ext}(t) \) to the structures in the vicinity of the joint.

The determination of resultant external joint forces and moments is well defined if the segments are treated as rigid bodies. The 'inverse dynamic' approach (Andrews, 1974, 1982) may be utilized to calculate the resultant external joint forces and moments.

The distribution of the resultant joint moments and forces to the individual force-carrying structures in the vicinity of a joint is more difficult. The human locomotor system is described as having more internal force-carrying structures (e.g., muscles, ligaments, capsules) than needed to produce or inhibit rotation around a joint. The different muscles acting around a joint have an infinite number of possibilities for producing a specific movement (Crowninshield and Brand, 1981) which mathematically results in an indeterminate system of equations.

The possible strategies to 'solve' this indeterminacy problem are currently concentrated into two groups, the reduction and the addition strategies. The reduction strategy 'solves' the indeterminacy problem by reducing the number of force-carrying structures crossing a joint to the number of equations available (or less). The result is a unique mathematical solution for the forces in these theoretical structures (Paul, 1965; Morrison, 1970; Baumann and Stucke, 1980; Procter, 1981; Denoth et al., 1985). The addition strategy 'solves' the indeterminacy problem by adding equations based on physiological considerations or mathematical optimization techniques (Paul, 1965; Morrison, 1970; Seireg and Arvikar, 1973; Pedotti et al., 1978; Crowninshield and Brand, 1981; Pierrynowski, 1982; Herreg, 1985), neurophysiological considerations (Hatze, 1981; Denoth, 1986) or a combination of the above. The discussion strategy does not 'solve' the problem by providing one unique solution but rather discusses the various possibilities (Denoth, 1986). This strategy may have its merits for clinical discussions but is currently not widely studied and/or applied.

There may be a fourth strategy which could be called 'determinate' strategy which is not used at all currently. The idea is to assume that the load distribution is mechanically determined. One may suggest that there are enough mathematical equations to predict the internal force distribution and that the human musculo-skeletal system is not mechanically undetermined if all actual joints are used as 6 DOF (degrees of freedom) joints. The leg is a good example to illustrate this idea. At least three joints can be used at the level of the knee, the tibio-femoral joint, the patello-femoral joint and the proximal tibia-fibular joint. These three joints provide 18 equations which correspond to 18 anatomical structures for which force information can be estimated. The number of possible joints is even bigger at the level of the foot. If only the most prominent joints are included (from the tibio-talar and the distal tibia-fibular joints to the metatarsal-phalangeal joints) at least 15 joints can be identified which correspond to 90 anatomical structures crossing at least one of these joints for which forces can be estimated.

A substantial number of different models with various degrees of sophistication are currently used. In an attempt to analyze how sensitive some of the currently used models are to changes in input parameters, Herzog (1990) compared the muscle force estimates from three nonlinear optimal design models. He found that the estimated muscle forces 'depend heavily on the objective function' used and that 'small changes in the muscle variables caused dramatic changes in the muscle force estimates in at least one of the three optimal design models investigated'. The calculated differences were in some cases greater than 100% if comparing the smallest with the largest estimate of the three models for specific conditions.

The estimates of the muscle forces from the various models may, therefore, differ dramatically for a particular case, and it is currently not possible to use any of these estimates as a reliable indication for the actual magnitude of the internal forces. Attempts have been made to determine internal forces experimentally in vivo (Komi et al. (1987) and Gregor et al. (1987) for forces in the Achilles tendon; and Graichen and Bergman (1989) for forces at the hip joint). Such examples may be considered an excellent possibility for 'validating' a model. However, for anatomical/technical reasons they will be limited to a small number of anatomical structures in the human body, and for ethical reasons they may remain the exception.

The accurate in vivo determination of stress in the endangered or possibly overloaded anatomical structure may be considered as a prerequisite for the successful application of the 'cause-effect approach'. The discussion above indicates that this accurate determination is not possible with the methods currently available. This suggests that there may be some problems in the successful application of the 'cause-effect approach'.
To summarize (a), (b) and (c): it is currently not possible to determine internal stresses in anatomical structures or material properties of these structures with sufficient accuracy. A comparison of internal stresses (for which the errors may be bigger than 100 %) with the corresponding critical stress limits (for which the errors may be bigger than 100 %) as suggested in the third step of the 'cause-effect approach' would most likely provide erroneous results and conclusions and should not be expected to provide any help in the reduction of sports injuries. However, even if it would be possible to quantify accurately the stresses in and the critical limits of an anatomical structure, it still would be questionable whether the knowledge that the forces exceed the critical limits for a certain activity would contribute to a reduction of the frequency of injuries. As a matter of fact, this knowledge is already implicitly available in a number of sports injuries and does not seem to reduce the frequency of acute and/or overuse injuries. Other strategies must, therefore, be applied if the stresses estimated from model calculations are to help to reduce the number of sports injuries.

(d) Factors influencing stress

The knowledge of the factors influencing stress may be considered as being important for the possible reduction of sports injuries. If they are known, strategies can be developed for ensuring reduced internal stress in an endangered structure. Since the determination of the magnitude of the internal stress is not possible with sufficient accuracy and may not lead to an understanding of the important factors, other strategies must be found.

The 'comparison technique' is proposed for the analysis in one particular test subject of whether or not the forces or stresses in a specific anatomical structure are smaller for a specific condition A compared to another specific condition B. Examples for such a comparison technique can be found in sport shoes and/or shoe orthotics. Special sport shoes, insoles or orthotics are sometimes prescribed and/or used assuming that they reduce the local force in a particular structure of the locomotor system during sport activities. The comparison technique would therefore compare internal forces in a particular anatomical structure for shoe or orthotic A, and shoe or orthotic B. The comparison technique is based on the assumption that the influence of systematic errors which are inherently present in the estimates of internal forces may be reduced to an acceptable magnitude when determining the difference between internal forces for two comparable situations.

The comparison technique uses results from a model determining, for instance, the forces \( F_A \) and \( F_B \) for the two comparable situations A and B in one specific anatomical structure of interest where:

\[
F_A(\text{true}) = F_A(\text{meas}) + F_A(\text{error})
\]

\[
F_B(\text{true}) = F_B(\text{meas}) + F_B(\text{error})
\]

assuming that \( F_A(\text{error}) \approx F_B(\text{error}) \); therefore

\[
F_A(\text{true}) - F_B(\text{true}) \approx F_A(\text{meas}) - F_B(\text{meas}).
\]

The difference between the two internal forces measured in the experiment will be close to the true difference if the above assumptions are correct and the errors in the differences may be small enough to be neglected. The appropriateness of this assumption depends on the origin of the error. If the error is systematic the assumption may hold. If the error is random the assumption may not hold and the comparison technique is not applicable. Evidence for the appropriateness of this assumption is, therefore, necessary if the comparison technique is applied.

The comparison technique allows the discussion of the effect of protective construction strategies or suggested treatment modalities by analyzing whether or not a particular strategy may reduce for one subject, or even for a group of athletes, the forces or stresses in the endangered structures.

Studies comparing internal forces have been used in a rather limited number of cases of research-determining factors influencing load in anatomical structures. Baumann and Stucke (1980) presented a model for the estimation of forces in the ankle joint, the medial triceps surae, the Achilles tendon and the knee joint and compared the estimated forces for various sports activities. Misovich and Cavanagh (1984) used a model of the human foot studying the shoe/foot interaction in the absorption of impact forces and applied it, for instance, to the comparison of impact forces for open and closed cell foams of shoe soles. They found that open cell foam absorbs less than 10% of the energy absorbed by closed cell foam. Denoth (1986) used a model for the foot and lower leg to compare internal forces in the ankle joint for differences in the length of the moment arm between the resultant ground reaction force and an idealized subtalar joint axis. He found that internal impact force peaks changed only marginally for changes in the moment arm and that the time interval between touchdown and peak impact force doubles when changing the moment arm from 0 to 4 cm. This model was later expanded (Stacoff et al., 1988) for the comparison of forces in muscles on the medial and/or lateral side of the idealized subtalar joint axis. The results of these comparisons suggest that changes in the magnitude of the muscle forces are about 40–50 % for differences in moment arms as they are currently existing in running shoes.

The basic understanding of the mechanism to be discussed is a prerequisite for the development of a reasonable biomechanical model. The models discussed above used already existing knowledge which was based on previous experimental data and/or theoretical considerations. Such models can be used to improve the conceptual understanding of the importance of factors influencing stress which are already incorporated as variables in the model. (Note that increased complexity does not make such models necessarily more powerful.)
Results derived from models when based on a 'comparison technique' may have had an influence on changes of sport shoe construction. The current use of closed cell foam for shoe soles has been partially influenced by the comparison of impact absorption with the model of Misevich and Cavanagh (1984). The change of the wide flared heels of sport shoes in the late seventies to the heel constructions which have now little, no or even negative flare have been partially influenced by the results from model studies as described above (Denoth, 1986; Stacoff et al., 1988). Thus, findings from comparative model studies have had a direct effect on the construction of sports shoes and consequently may have had an indirect effect on the reduction of the number of sports injuries. However, conclusive evidence for such a reduction is missing.

To summarize (d): the comparison of forces or stresses in anatomical structures of the locomotor system or in structures of the sport shoe produced findings which have been applied in the construction of new sport shoes. The evidence that these new shoe constructions in fact do reduce the frequency of injuries is missing. However, it is speculated that research using the 'comparison technique' for the analysis of the factors influencing internal forces and stresses has the potential to reduce the frequency of injuries. The 'cause-effect approach' may, therefore, be successfully applied if the estimates of internal forces are compared for systematical changes of important variables.

AN 'EMPIRICAL APPROACH'

The approach which will be referred to as the 'empirical approach' is based on the assumption that the accurate knowledge of the mechanisms responsible for an injury is not a necessary prerequisite to affect the number of sport injuries and that instead correlations and/or probabilities may be used in the attempt to reduce such injuries.

The procedure when approaching the problem from this perspective is to determine the factors which may have an effect on the stress in a particular anatomical structure or region while performing this activity. For example with running, which will be used predominantly in the following, one realizes that there are only a few possibilities for the reduction of internal stress. Two of the most obvious ones are the surface and the shoe, of which the shoe seems to be the easier one to change. The following discussion will, therefore, use the sport shoe as an example. However, the conclusions are general in nature and similar approaches have been used, for instance, for sports equipment (Ekstrand, 1982) and for muscular joint stability (Tropp, 1985).

In order to contribute towards a reduction in the frequency of sport injuries, it could be proposed that biomechanical research based on the empirical approach should include the following five steps. It should analyze the possible relationship between the shoe construction and type and/or frequency of sport injuries, the possible relationship between kinetics/kinematics and particular sport injuries, and the influence of shoe construction on the kinetics/kinematics, it should list the demands to be satisfied by the shoe construction, and finally it should verify that shoes constructed according to the above findings do in fact reduce the frequency of injuries. The methods proposed for these five steps and some of the findings of corresponding research are discussed below.

(a) Shoes — injuries

It has been shown that the type of shoe used for a specific sports activity has had an influence on the type and/or the frequency of injuries. Yorg and Quedenfeld (1971) carried out a retrospective study of knee and ankle injuries of athletes in high school (American) football leagues. They showed that the frequency and severity of these injuries was higher for athletes using football shoes with seven 19 mm cleats (9.5 mm diameter) than for athletes using shoes with fourteen 9.5 mm cleats (12.5 mm diameter). Luethi (1983) and Luethi et al. (1986) studied the influence of shoes in a prospective study in tennis. They distributed two different shoe models which were available on the market at the time of the experiment to a group of healthy tennis players and monitored the overuse injuries occurring during the following three months of activity. They found a significant difference in the relative number of injuries for the two shoe groups (32.6% for one and 47.1% for the other shoe) as well as a difference in the type and location of the injuries. Both studies indicate that the shoe in fact does influence type and frequency of sports injuries.

From a methodological point of view it may be stressed that information on a possible relationship between shoes and injuries may be gathered with a prospective as well as with a retrospective approach.

(b) Kinetics/kinematics — injuries

Information on a possible relationship between kinetics/kinematics and injuries should ideally be gained from studies with a prospective design. Studies with a retrospective design analyzing the movement of injured subjects (Viitasalo and Kvist, 1983; Andreasen and Peterson, 1986; Kujala et al., 1987) may have their merits in pointing out a certain direction for a possible correlation. However, they never can decide whether differences in kinetics/kinematics are due to the injury or whether the injury is due to the different kinetics/kinematics.

Prospective studies analyzing the possible correlation between kinetics/kinematics and particular injuries are not numerous. For tennis, Luethi (1983) showed that subjects with injuries had performed, prior to injury, often excessive or inhibited supination in a standardized sideways movement. Bahlsen (1988) compared kinetics/kinematics quantitated at the beginning of a six month prospective study period for
runners with patella-femoral syndrome (PFS) and runners with no injuries. He found that subjects with PFS showed significantly more pronation in the foot during midstance in running than subjects who did not become injured in this period. The two studies suggest that excessive pro- and/or supination may be a risk factor for specific injuries or groups of injuries, or in a more general sense that there is a correlation between kinematics and sports injuries.

There is no direct prospective but only indirect evidence that the kinetics are also correlated with the development of injuries and/or degenerative phenomena. Impact forces have been speculated or shown to be related to cartilage degeneration (Radin et al., 1973, 1982), fatigue fracture and shin splint (James et al., 1978; Clement et al., 1981; Segesser and Stacoff, 1981; Andreasen and Peterson, 1986). Achilles tendon problems (Jorgensen, 1985) and hematological changes (Falsetti et al., 1983). Additionally, Jorgensen and Hansen (1989) showed in a prospective study with soldiers an increased frequency of overuse injuries for subjects with low shock absorbency in the heel pad. However, prospective studies indicating a correlation between the kinetics (e.g. internal or external impact forces) are not known.

The findings of the studies analyzing the correlation between kinetics/kinematics and sports injuries indicate that correlations between the kinematics and the occurrence of sports injuries can be found in certain cases. Additionally, there is speculation that the magnitude and/or frequency of impact forces may be a risk factor for certain sports injuries. However, the evidence for such a correlation between the kinetics and the occurrence of certain sports injuries is still missing.

(c) Shoe construction—kinetics/kinematics

Research publications analyzing how shoe construction may influence kinetics/kinematics outnumber the publications in the other load analysis related fields. The results indicate that shoe construction in fact has a dominant effect on the kinetics/kinematics during movement (Nigg et al., 1978; Cavanagh, 1980; Frederick et al., 1984; Kaelin et al., 1985; Nigg and Morlock, 1987).

Results of projects analyzing the influence of various strategies of shoe construction on kinetics/kinematics were sometimes surprising. Two examples should illustrate this in more detail:

1. The external vertical impact force peak has been speculated to be one important factor in shoe design and numerous studies have concentrated on this topic. One possibility for influencing the magnitude of these vertical impact force peaks seems to be the variation of the mechanical stiffness of the midsole. However, changes in midsole hardness of running shoes between shoes 25 and 55 does, surprisingly, not seem to affect the magnitude of the external vertical impact force peak significantly (Clarke et al., 1983; Nigg et al., 1983; Snell et al., 1983; Kaelin et al., 1985; Luethi et al., 1987). But changes in midsole hardness do affect the pronation of the foot during the landing phase. Shoes with soft midsole material produce less initial pronation than shoes with hard insoles. These results have been explained with a change in the geometry of foot and leg during landing and/or the changed movement of the foot during initial contact with the ground (Kaelin et al., 1985).

2. Excessive pronation and/or supination has been shown to be correlated with overuse injuries. One concept for reducing or avoiding excessive pronation or supination is the stiffening of the rearfoot of the shoe. Consequently, 'heel stabilizers' have been introduced to reduce, for instance, pronation in running. However, shoes with heel stabilizers have been shown to produce higher initial pronation, but lower vertical impact force peak, than shoes with no heel stabilizers (Fig. 1). Additionally, maximum pronation, measured with a two-dimensional method, does not differ for shoes with and without heel stabilizers.

Both examples illustrate that caution is necessary in the development of strategies to improve the quality of a shoe with respect to possible load reduction, and that intuition may not always lead to the correct way. However, it is obvious that empirical biomechanical research analyzing the correlation between shoe construction and kinetics/kinematics has had a significant impact on the development of sports shoes in the last 15 yr.

(d) Demands for shoe construction

There is no doubt that shoe construction significantly influences kinetics/kinematics during sports activities. Many strategies on how particular excessive kinetics/kinematics can be avoided are known and are currently applied. Demands on how sport shoes should be constructed to minimize stress in the locomotor system have been published for running shoes (Cavanagh, 1980; Nigg and Morlock, 1987), for tennis shoes (Nigg et al., 1987b) and for ski boots (Hauser and Schaff, 1987). They are quite general in their concepts, still leaving room for technical improvement.

(e) Verification

The last step, the verification that the injury frequency in the shoes developed following biomechanical findings is in fact reduced, requires a prospective research approach. Frequency and type of injuries must be compared for groups using the 'new' and the 'old' shoes. This procedure has some critical aspects since it is ethically not acceptable to proceed with such an experiment if based on some evidence it is hypothesized that one shoe type will produce significantly more injuries than the other one. Other methods of verification must, therefore, be found. Consequently, studies verifying that new shoe constructions are connected with less injuries than previous constructions are missing.

An indirect possibility providing some limited evidence may be to analyze the injury frequency in particular sports over time. Data for injury frequencies for the
Load analysis to reduce the frequency of sports injuries

Fig. 1. The effect of a heel stabilizer on the vertical impact force peak, $F_{\text{V,I}}$, the initial pronation, $\Delta \beta_{\text{ini}}$, and the total pronation, $\Delta \beta_{\text{pro}}$.

last 15-25 yr are available from different sources. Injury frequencies for running over the last 20 yr show no significant trend of a reduction in general but a significant trend in the increase in the relative incidence of knee injuries (Fig. 2). However, methodological differences make it difficult to compare these data. Various authors did not use the same injury definitions and the sophistication of diagnosis of sports injuries has drastically improved in the last 20 yr (Friedmann, 1986). It cannot, therefore, be derived conclusively whether the results for injury type and/or frequency are due to actual changes or are merely influenced by differences in methodology.

Epidemiological studies in skiing seem to be more coordinated so that injury frequencies may be compared. Injury frequencies in skiing indicate a significant reduction during the last 20 yr (Johnson and Ettlinger, 1982: Hauser et al., 1985). All locations in the body except the knee show a reduced injury frequency if related to the number of hours skied. It is speculated that these changes are mainly due to changes in the release bindings and changes in ski boot construction.

It is obviously not appropriate to conclude from these data that changes in running shoe construction, which were partially based on biomechanical research, did in fact reduce the frequency of running injuries. The data for skiing seem to be stronger evidence for the effect of empirical biomechanical research on the reduction of sports injuries. However, the data still include many other possible factors than the shoe, and it is currently not possible to connect the reduction of injuries in skiing to one or only a few factors studied in biomechanical research. The conclusive evidence that sport shoes developed after biomechanical research findings did in fact reduce the frequency of sport injuries is, therefore, still missing.

Fig. 2. Relative frequency of knee injuries between 1971 and 1988 using studies on runners or patients (race data have not been included) based on data from Bahlsen (1988).

COMPARISON OF THE DISCUSSED APPROACHES

The 'cause-effect approach' and the 'empirical approach' differ in how they deal with the factors which influence the occurrence of injuries. The 'cause-effect approach' uses the estimated internal stress in the anatomical structures of interest. However, the estimation and the comparison of the stress with the critical stress limits still has too many methodological problems to be applied in actual situations in sports activities. The possible errors may exceed 100% for the stresses as well as for the critical stress limits, and results from such comparisons may lead to erroneous speculations or conclusions. The review indicates that research limited to the estimation of the magnitude of internal stresses (steps (a), (b) and (c) of the 'cause-effect approach') has not yet contributed to a reduction of the frequency of injuries and it may be questionable whether it even has the potential to contribute to a possible reduction at all, since the
information provided that the stress is excessive was already implicitly available in the injury frequencies.

However, stresses estimated with models can be used when analyzing the differences of stresses for situations which can be compared. The procedure is based on a 'comparison technique' which uses the assumption that systematic errors may be reduced to an acceptable level when analyzing differences in internal stresses. The review of this technique indicates that results from such comparisons have been used in load analysis specifically in the development of new sport shoe constructions. The evidence for an actual reduction of the frequency of injuries due to these changes is missing. However, it is proposed that the comparison technique has the potential for contributing to a reduction of sports injuries.

The 'empirical approach' is based on the assumption that the knowledge of the mechanics of a sports injury is not a prerequisite for the reduction of the injury frequency. The review of this approach showed that results from empirical studies have been frequently in the development of new shoe constructions. There are indications that empirical research has already contributed to a reduction in the frequency of sports injuries. However, the conclusive evidence for an actual reduction due to these changes is missing. It is proposed that the 'empirical approach' has the potential to contribute to a reduction of sports injuries. However, the empirical approach does in many cases not provide a comprehensive understanding of the mechanisms related to the etiology of sport injuries.

The purpose of this review was not to demonstrate the superiority of one specific approach over the other but rather to outline the strengths and/or weaknesses of some possible approaches which may be used in an attempt to contribute to the reduction of sport injuries. The subdivision into the two 'approaches' has been arbitrary and it is obvious that they have some aspects in common and that they may complement each other in some aspects. The final conclusion, therefore, is not to select one or the other approach but to use both of them appropriately when they promise to contribute to the final goal, the reduction of sports injuries.

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APPENDIX

Definitions

Sports injury: micro- or macrodamage of a biological structure of the human locomotor system due to sports activity.

Acute injury: an injury as a result of one excessive force application to the anatomical structure of interest.

Overuse injury: an injury as a result of repeated force application to the anatomical structure of interest.

External force: a force acting externally to the locomotor system.

Internal force: a force acting on an internal anatomical structure (e.g. tendon, bone) of the locomotor system.

Impact force: a force which is the result of a collision between one part of the locomotor system and the environment (e.g. collision between foot and ground) and which reaches its peak value earlier than 50 ms after first contact.

Active force: a force which is the result of controlled muscle activity and which reaches its peak value later than 50 ms after first contact of the locomotor system with the environment.

Critical force (for acute injury): magnitude of a single force for which the anatomical structure of interest is damaged.

Critical force (for overuse injury): magnitude of a repeated force for which the anatomical structure of interest is damaged.