OPTIMAL FRICTIONAL PROPERTIES FOR SPORT SHOES AND SPORT SURFACES

E. C. Frederick

Exeter Research, Inc.
Exeter, NH

The rigors of sport require sufficient friction between the sole of the shoe and the surface to provide sure footing for the player. When the sole of a sport shoe and a surface come in contact with one another two main types of friction determine how easy it will be for relative movement to occur between the two. Translational friction determines how much horizontal force will be needed to cause the shoe to slide over the surface. Rotational friction determines how much force must be applied as a moment of force to cause the shoe to pivot on the surface. Both types have relevance in a discussion of the role of friction in sports. And, it appears, both are related.

In translational friction measurements, the coefficient of friction is defined as the ratio of the *normal* force (normal = perpendicular to the surface) to the horizontal force required to produce movement between the two surfaces. The normal force is the force pushing the two surfaces together. On a level surface the normal force is the vertical component of the force between the surface and the shoe. The horizontal component of force in this situation is known as the frictional force. A simple equation describes that relationship:

$$F_f = \mu_s \cdot N \quad \text{or,} \quad \mu_s = F_f / N \quad \text{[static friction]} \qquad (1)$$

where F_f = frictional force, the horizontal force
μ_s = the coefficient of translational friction, static
and N = the normal force.

This relationship simply explained means that if a person weighing 150 pounds is standing on a surface with a μ_s of 0.50 that it will take 50% of that 150 pound normal force, or 75 lbs, of a horizontal force to cause sliding between the shoe and the surface. A μ_s of 0.10 would require only 10% or 15 lbs horizontal force to cause sliding. A μ_s of 0.90 on the other hand would require 135 lbs of horizontal force to produce sliding.

Once the two surfaces (shoe sole and playing surface) start sliding it becomes slightly easier to maintain or to increase the speed of sliding. This is exemplified by the skidding of a car. A non-skidding rolling tire has a relatively high static friction between tire and road which can effectively slow the car down when the brakes are applied. A skidding tire, however, has a lower frictional coefficient and so it is harder to stop the car when the brakes are applied.

The coefficient that defines the ratio of friction during sliding is called the dynamic translational friction coefficient, and it is signified by the symbol μ_d. The physics describing this relationship is much more complex than that for static friction but it is generally accepted that the same ratio of horizontal to normal force can define μ_d when two flat and dry surfaces are involved.

The coefficient μ_d is usually less than μ_s, but how much less depends on the two surfaces involved. It has been our experience, however, that the two coefficients are nearly the same or indistinguishable when most sport surfaces and shoes with synthetic soles are involved.

MEASURING TRANSLATIONAL FRICTION

These coefficients can be measured using physical tests, or by performing carefully controlled experiments using human subjects. In general, physical tests yield higher coefficients than subject tests (Stuke et al., 1984). This is because humans try to adjust their movement pattern to compensate for excessively high or low friction. Measurements made with carefully designed mechanical tests are preferable because they allow for more control over the multiple factors that affect frictional measurements, although great care must be taken to be certain that the test parameters represent the real circumstances athletes will encounter when working out and competing.

Experts seem to agree that a coefficient of 0.8 for μ_s provides sufficient traction for even the most powerful athletic movement. The rationale for this has been clearly articulated by Valiant (1987). Coefficients higher than this are regarded as unnecessary and may be unsafe. The relationship between safety and frictional properties will be discussed in a review of the epidemiological literature presented further on in this report.

ROTATIONAL FRICTION

Measurements of rotational friction do not have coefficients but instead rely on the relative values of free moments of rotation between the shoe and surface. A moment is a force applied via a lever arm which acts to produce rotation or a tendency to rotate. Moments are sometimes incorrectly called torques. Torque refers specifically to a turning moment that produces only torsion, or a twisting of the structure it is applied to. Moment is a more inclusive and accurate term to describe what is going on at the interface between shoe and surface. As the shoe rotates or tends to rotate on the surface, torsion is sometimes the result, but this is not the only type of strain produced.

When comparing various surface and shoe combinations, researchers generally use the peak free moment of ground reaction force to describe the rotational frictional character of the combination. This value is the peak moment required to produce a rotation (or *attempt* to produce a rotation in some special cases). Surfaces with higher rotational friction demonstrate greater peak moments during pivoting. Surfaces with lower rotational friction show lower peak moments. For example, executing a 180° pivot on a wooden basketball court while wearing gym socks would result in a peak free moment of rotation (M_z) of about 3 Newton·meters (Nm). Putting on a conventional basketball shoe would add rotational friction such that performing the same maneuver would produce an Mz as high as about 13 Nm (Valiant, et al., 1986). Performing these same movements on synthetic turf, an abrasive carpet type surface, result in Mz data as high as 33 Nm (see Figure 1).

As with translational friction, rotational friction measurements can be made using physical test apparatus or using human subjects. Physical tests of rotational friction produce results over a wide spectrum, but these mechanical tests generally yield higher peak moment scores than the human subject tests (see Figure 1), and the differences tend to be more pronounced as rotational friction increases.

For similar reasons to those cited for translational measurements, the mechanical tests of rotational friction are preferred by researchers trying to evaluate the safety and performance aspects of playing surfaces. Because tests using subjects produce M_z's that are generally lower than physical tests, but in a non-systematic way, it is difficult to interpret the results of human subject tests. It is the feeling of this author and of many of his colleagues currently working in this area of biomechanics that subject tests alone should not be used for the evaluation of the rotational frictional aspects of surface safety and performance. If only one test method is to be used, a physical test would be preferred.

INTERRELATIONSHIP OF FRICTIONAL COMPONENTS

Although the translational and rotational components of friction are measured differently, they are not independent parameters. Important relationships can be found in the equation for the moment of rotation (Schlaepfer et al., 1983) derived from Coulomb's Law.

$$M = \mu_d \cdot \int_A p(r,\theta) \cdot r^2 \, \Delta r \Delta\theta \qquad \text{[moment of rotation]} \qquad (2)$$

where μ_d = translational friction coefficient, dynamic
p = vertical pressure
r = polar coordinate
θ = polar coordinate (with respect to center of rotation)
A = contact area
and M = moment of rotation

This relationship is important because it shows that pressure is a factor and that another major factor influencing the moment of rotation is the coefficient of dynamic translational fiction, μd.

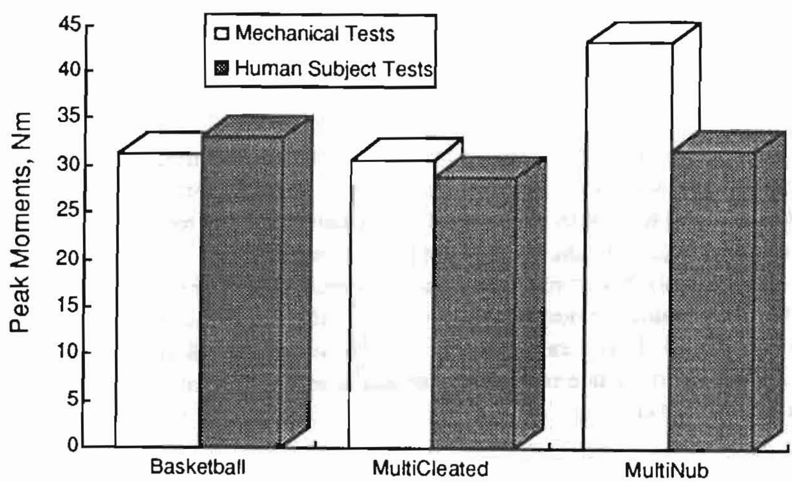

Figure 1. Mechanical Tests of Rotational Friction versus Tests Done with Human Subjects. The test method for the human subject trials was derived from that of Michel (1978). These data were all gathered on a synthetic turf surface. The shoes were: Basketball, a typical basketball shoe with a relatively low profile sole configuration; MultiCleated, a soccer style boot with molded cleats; and MultiNub, a synthetic turf shoe with more than 100 small rubber nubs protruding from the bottom of the sole. As a rule, human subject tests result in lower measured peak moments, especially when friction is relatively high.

In fact there is a positive correlation between the μ_d and the rotational friction measured between given combinations of shoe and surface. This correlation however is not 100% and there appear to be other influencing factors that give sport shoe and surface designers potential avenues for providing relatively high translational and low rotational friction.

Indeed it is hard to generalize about the frictional interactions of sport shoe types and sport surfaces. For example, people often consider cleated shoes to have high frictional characteristics because of the interlocking with the surface that occurs (van Gheluwe, 1983; Valiant et al., 1985). However, we know that high translational coefficients (μ_d = 0.95) can also be found for court shoes on polyurethane surfaces even though they are generally considered to have lower friction.

Many surfaces have coefficients well above the 0.8 maximum value discussed above when tested with typical sport shoes. This high translational friction might introduce a higher than necessary risk of injury.

More to the point, the rotational frictional properties may also be higher than necessary primarily because of the above interrelationship. Analysis of translational frictional properties and the peak moments of rotation with various shoe/surface combinations can lead us to some very interesting observations.

IS THERE AN OPTIMAL SOLUTION?

Contrary to what seems logical to the non-professional eye, cutting movements and other directional changes are purely translational. They require only that the shoe does not slip on the surface during the movement in the plane in which horizontal forces are directed. Rotation is not an issue in preventing slipping. We do not spin on the foot when changing direction or accelerating while running.

In theory, a shoe/surface with adequate translational friction (μ_d= 0.8) could have an M_z approaching zero with no effect on performance. In practice, however, because rotational and translational friction are linked, some minimal rotational friction is a necessary consequence. Also, the pronation and supination that occur during normal foot contact produce net moments between shoe and surface that might cause an uncomfortable, slight spin of the foot during each contact if the rotational friction of the shoe/surface is not high enough to control (but not prevent) it.

Free moments have been measured during running and reported to be about 12 Nm as a maximum value for normal subjects (calculated from data presented by Holden and Cavanagh, 1986). This means that a shoe/surface with a peak free moment of 12Nm will provide enough resistance to rotation to minimize the natural pivoting of the foot during normal ground contact.

HOW MUCH ROTATIONAL FRICTION IS ENOUGH?

Some minimal rotational friction is likely required, however, resistances to rotation higher than that minimum are unnecessary and may be dangerous if the moment produced by the body is high enough to put untoward rotational strain on bone and soft tissues. We have picked the numbers 10 to 12 Nm because they represent normal peak values for asymptomatic humans walking and running. A normalization scheme should be developed to relate these absolute values to atypical humans. The absolute values for peak free moment for exceptionally large or small people should vary above and below the 10 to 12 N·m values for an average population, however, the normalized values should be similar. The best value for minimal rotational friction may be less than what we have chosen as a first approximation, but it is hard to imagine that it would be higher.

ROTATIONAL FRICTION, SHOE DESIGN AND KNEE INJURY

There is no dispute that excessive rotation at the knee joint can cause injury. The anatomical locking, the "screw-home motion", that normally stabilizes the knee joint, occurs only during slight flexion. Once the knee has flexed appreciably it must depend upon ligaments and muscles for stability. So, tendons and ligaments are under particular strain because they will take up the rotational stress in the knee if the joint is flexed, as is the case in most traumatic knee injuries.

A further contributing factor to knee injuries is having the foot rolled onto the medial border or onto the outside edge of the sole of the shoe. This means that pressures and therefore the rotational moments between shoe and surface would be higher (see Equation 2) even than what we would have measured in our experiments with the foot flat.

The net result of these factors is a foot that may be fixed and resists rotation or sliding. These rotational moments may produce a strain on the structures in the anatomical chain that would yield to the increasing stress. In many unfortunate cases it seems the knee yields before the fixed foot and shoe/surface. Our suggestion is not a new one, but it has yet to be successfully applied to a performance sport shoe. The idea is a straightforward optimal combination of two related factors: make rotational friction as low as possible, just below a minimal threshold, and make translational friction just a touch higher than its minimal required value.

A similar philosophy of controlled rotational friction was pursued in the 1960's in the design of a football shoe designed to reduce knee and ankle injuries. Because knee injuries are known to result from excessive rotational friction between the shoe and surface (see numerous papers by Torg; as well as Cameron and Davis, 1973; and Rowe et al., 1969) this shoe incorporated a swivel plate which allowed easy rotation about a point under the ball of the foot.

The shoe was designed with a sealed metallic forefoot turntable with four molded cleats on the outside of the turntable. The swivel plate's cleats allowed for adequate translational friction, to permit the athlete to make directional changes and to accelerate and decelerate without slipping. Epidemiological studies showed a several fold decrease in knee injuries when football players wore the swivel shoe (Cameron and Davis, 1973). Other shoe designs which lower the rotational friction have also been remarkably successful in reducing the frequency of traumatic knee injury (Gibbs,1970; Rowe, 1969). It is also worth noting that baseball shoes are a conspicuous example of the application of this principle. They are designed with their cleats oriented along the circumference of a circle describing the rotation about the forefoot. This design maintains translational friction while minimizing rotational friction.

The fact that safety was increased without significant detriment to performance by using the swivel shoe design is important. But it is also significant that the shoe's designers desired a certain minimal rotational resistance rather than opting for free rotation. Measurements of the peak moment of rotation of a swivel shoe were made at Penn State University's Sports Research Institute on a physical test apparatus. The peak free moment was 10.7 Nm (Bonstigl et al., 1975). Had these tests been made with human subjects it is likely that the moments would have been lower, but by an unknown amount. It is our experience that surfaces with higher physically measured moments produce more adaptation in the human subject tests; and when low rotational friction is found the human tests are much more similar to the physical test values. Does this suggest that there is a threshold for adaptation? Is there a certain critical level of rotational friction below which no adaptation is required? This is a question that begs to be attacked experimentally. But we can draw some preliminary conclusions from the data we have in hand.

What these data suggest is that translational friction is the critical element in performance on sport surfaces and rotational friction is the critical element in injury prevention. Rotational friction between surface and shoe should be as low as possible without producing excessive (some slight rotation is desirable) or uncomfortable twisting movements. We feel that peak free moments between shoe and surface do not need to be higher than about 10 to 12 Nm.

For example, these values are close to what a typical basketball shoe would show when measured with human subjects on a hardwood floor. No one would argue that basketball players are inhibited in their ability to perform directional changes, and they do not have the high incidence of traumatic knee injuries found in sports such as soccer and football where rotational friction values between shoe and surface are often much higher and foot fixation can occur.

Further justification for this point of view is found in the reports of Nigg and several collaborators published in the late 70's and early 80's. In surveys of injuries to tennis players on surfaces with different frictional characteristics, they found that surfaces with higher friction both translational and rotational brought with them a significantly higher risk of injury. The higher the friction the more injury, supporting the notion that friction should be as low as possible without significantly impairing performance.

CONCLUSIONS

1. High rotational friction on sport surfaces has been shown to cause an increased incidence of traumatic injury to the knee and ankle.
2. Many sport surfaces have greater translational and rotational friction than required for the effective performance of sports movements.
3. Excessive rotational friction, as evidenced by a peak free moment of rotation significantly greater than 10 to 12 Nm, may put athletes at risk.
4. Sport shoe designs, that have a translational friction of 0.8 with typical surfaces on which they are used and exhibit minimal rotational friction, should allow maximal performance while minimizing the risk of injury.

SUMMARY

Traumatic injuries are often the result of excessive torsional strain to the joint's soft tissues. A common mechanism underlying these torsional injuries is foot fixation accompanied by continued rotation of the structures above the foot. The knee is especially vulnerable. This situation has been clearly demonstrated in the etiology of cartilage and ligament trauma. Because of this factor, high rotational friction on sport surfaces has been linked to an increased incidence of traumatic injury to the knee and ankle.

It is all too common for the combined design of shoe and surface to produce greater translational and rotational friction than required for the effective performance of sports movements. This review makes the case that excessive rotational friction

results when shoe and surface show a peak free moment of rotation significantly greater than 10 to 12 Nm. Rotational friction higher than this level introduces an increased likelihood of injury due to excessive torsional strain to the knee joint. A surprising number of sport surfaces produce such excessive rotational friction when tested with typical "off-the-shelf" sport shoes. We recommend that cleated and court shoe designers develop shoes which produce rotational friction free moments of less than 10 to 12Nm when tested on typical playing surfaces. In order to maintain minimal translational friction values of 0.8 in the same shoes it may be necessary to develop special sole designs to accomplish this combination of safety and performance.

REFERENCES

Bonstigl, R. W., Morehouse, C. A., Niebel, B. W. (1975). Torques developed by different types of shoes on various types of playing surfaces. Med Sci Sports Exerc 7:127-131.

Cameron, B. and Davis, O. (1973). The swivel football shoe: A controlled study. AMPER Sports Med 1(1):16-27.

Gibbs, R. W. (1970). A nine-year study of football incurred knee injuries at Harvard, testing the validity of the Hanley Heel Concept. J Am Coll Health Assoc 18:345-346.

Holden, J. P. and Cavanagh, P. R. (1986). The free moment of ground reaction in distance running and its changes with pronation. Proceedings of the 1986 North American Congress on Biomechanics, pp. 209-210.

Luethi, S. and Nigg, B. M. (1985). The influence of different shoe constructions on discomfort and pain in tennis. In Biomechanics IX -B. D. A. Winter, R. W. Norman, R. P. Wells, K. C. Hayes, A. E. Patla (eds.). Champaign: Human Kinetics Publishers. pp. 149-153.

Luethi, S., Frederick, E. C., Hawes, M. R., Nigg, B. M. (1986). Influence of shoe construction on lower extremity kinematics and load during lateral movements in tennis. Int J Sports Biomech 2 (3):166-174.

Michel, H. (1978). Drehbewegungen auf Bodenbelägen (Rotation on surfaces). Master's Thesis ETH Zurich

Nigg, B. M. (ed.). (1986). Biomechanics of Running Shoes. Champaign, Il: Human Kinetics Publishers.

Nigg, B. M., Denoth, J., Kerr, B., Luethi, S., Smith, D., Stacoff, A. (1984). Load, sport shoes and playing surfaces. In Sport Shoes and Playing Surfaces. E. C. Frederick (ed.). pp. 1-23. Champaign: Human Kinetics Publishers.

Nigg, B. M., Denoth, J., Neukomm, P. A., Segesser, B. (1978). Biomechanische Aspekte zu Sportplatzbelagen. Zurich: Juris Verlag.

Nigg, B. M. and Denoth, J. (1980). Sportplatzbeläge. Zurich: Juris Verlag

Nigg, B. M., E. C. Frederick, M. Hawes, S. Luethi. (1986). Factors influencing short term pain and injury in tennis. Int J Sports Biomech 2(3):156-165.

Rowe, M. (1969). Varsity Football knee and ankle injury. NY State J Med 69(12):3000-3003.
Schlaepfer, F. E., Unold, E., Nigg, B. M. (1983). The frictional characteristics of tennis shoes. In Biomechanical Aspects of Sport Shoes and Playing Surfaces. B. M. Nigg, B. A. Kerr (eds.). pp. 153-160. Calgary: The University of Calgary, Alberta.

Stuke, H., Baudzus, W., Baumann, W. (1984). On friction characteristics of playing surfaces. In Sport Shoes and Playing Surfaces. E. C. Frederick (ed.). pp. 87-97. Champaign, IL: Human Kinetics Publishers.

Torg, J. S. and Quedenfeld, L. (1971). Effect of shoe type and cleat length on incidence and severity of knee injuries among high school football players. Res Quart 42:203-211.

Torg, J. S. and Quedenfeld, T. (1973). Knee and ankle injuries traced to shoes and cleats. Phys and Sportsmed 1(9):39-43.

Torg, J. S. Quedenfeld, T.C., Landau, S. (1974). The shoe-surface interface and its relationship to football knee injuries. J Sports Med 2(5): 261-269.

Torg, J. S., et al. (1973). Football shoe and playing surfaces: from safe to unsafe. Phys and Sportsmed 1(11):51-54.

Valiant, G. A., Cooper, L. B., McGuirk, T. (1986). Measurements of the rotational friction of court shoes on an oak hardwood playing surface. Proceedings of the North American Congress on Biomechanics, pp. 295-296

Valiant, G. A., McGuirk, T., McMahon, T. A., Frederick, E. C. (1985). Static friction characteristics of cleated outsole samples. Med Sci Sports Exer 17(2):156.

Valiant, G.A. (1987). Ground reaction forces developed on artificial turf. Proceedings of first World Congress of Science and Medicine in Football. Reilly and Lees (eds.). London: E&FN Spon.

Van Gheluwe, B., Deporte, E., Hebbelinck, M. (1983). Frictional forces and torques of soccer shoes on artificial turf. In Biomechanical Aspects of Sport Shoes and Playing Surfaces. B. M. Nigg and B. A. Kerr (eds.). pp.161-168. Calgary: The University of Calgary, Alberta.