biodynamics

Lateral stability in sideward cutting movements

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ABSTRACT

STACOFF, A., J. STEGER, E. STÜSSI, and C. REINSCHMIDT. Lateral stability in sideward cutting movements. *Med. Sci. Sports Exerc.*, Vol. 28, No. 3, pp. 350–358, 1996. Sideward cutting movements occur frequently in sports activities, such as basketball, soccer, and tennis. These activities show a high incidence of injuries to the lateral aspect of the ankle. Consequently, the lateral stability of sport shoes seems important. The purpose of this study was to show the effect of different shoe sole properties (hardness, thickness, torsional stiffness) and designs on the lateral stability during sideward cutting movements. A film analysis was conducted including 12 subjects performing a cutting movement barefoot and with five different pairs of shoes each filmed in the frontal plane. A standard film analysis was conducted; for the statistical analysis, various parameters such as the range of motion in inversion and the angular velocity of the rearfoot were used. The results showed a large difference between the barefoot and shod conditions with respect to the lateral stability. Two shoes performed significantly better ($P < 0.05$) than the others with a decreased inversion movement and less slipping inside the shoe. The two shoes differed mainly in the shoe sole design (hollow inner core) and the upper (high-cut). It is concluded that lateral stability may be improved by altering the properties and design of the shoe sole as well as the upper.

REARFOOT MOVEMENT, SPORTS INJURIES, SHOE DESIGN, ANKLE JOINT, INVERSION, SUPINATION, ANKLE SPRAIN

Injury statistics show that ankle injuries such as ankle sprains occur frequently in various sports activities (Table 1). Ankle sprains can occur as a result of excessive inversion movements at the subtalar joint outside the normal range of motion. To decrease the risk of injury, this inversion movement has to be controlled and reduced; in other words, lateral stability has to be provided (19,25,28,29).

A number of devices such as ankle braces, high-cut shoes, and taping are available to reduce the movement at the subtalar joint, and consequently improve ankle stability (2,8,14,17,26). These devices are externally fixed over the ankle; however, a change of the shoe sole design or of its properties is not considered.

Lateral cutting movements are very frequent in a number of sports activities (12,25), particularly basketball, volleyball, tennis, soccer, and European handball. Typically, during such a movement, the medial side of the shoe sole touches the ground first, producing a large lever relative to the subtalar joint axis (Fig. 1). The magnitude of this lever depends on the design and the properties of the shoe sole (10,21,25).

The purpose of this study was to show the kinematic effects of different shoe sole designs and properties on the lateral stability at the ankle during sideward cutting movements.

Basic Considerations

Injury mechanism. An ankle sprain occurs when the external inversion moment at the ankle is larger than the internal eversion moment provided by structures such as muscles (foot everters) and ligaments. The external moment depends on the acting force (ground reaction) and the leverage between the point of application and the point of rotation at the ankle joint (Fig. 1).

With respect to leverage, the barefoot situation has an advantage over the shod situation. The shoe sole increases the lever arm and as a consequence the moment about the subtalar joint. This was shown theoretically (21) as well as in a prospective study (10).

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TABLE 1. Relative frequency of ankle injuries.

Sports	Gender	Total No. of Injuries	Ankle Injuries (%)	Reference	Year(s)
All sports	Men and women	15212	20	Steinbrück (27)	1987
		10496	17	Segesser and Nigg (18)	1993
Baseball	Men	525	12	NCAA (11)	1989/90
Basketball	Men	769	31	NCAA (11)	1989/90
Basketball	Women	638	26	NCAA (11)	1989/90
Basketball	Men and women	658	28	Pfeifer et al. (15)	1992
Field hockey	Women	187–349	10–18	NCAA (11)	1987–91
Football	Men	1543–4956	15–16	NCAA (11)	1988–90
Handball (European)	Men	540	21	Leidinger et al. (9)	1990
Soccer	Men	112–288	17–21	Ekstrand and Tropp (3)	1990
Soccer	Men	527–981	17–21	NCAA (11)	1986–91
Soccer	Women	288–473	18–27	NCAA (11)	1986–91
Volleyball	Women	149–465	26–33	NCAA (11)	1984–91
Softball	Women	192	18	NCAA (11)	1989/90
Tennis	Men and women	2481	11	Nigg et al. (12)	1989

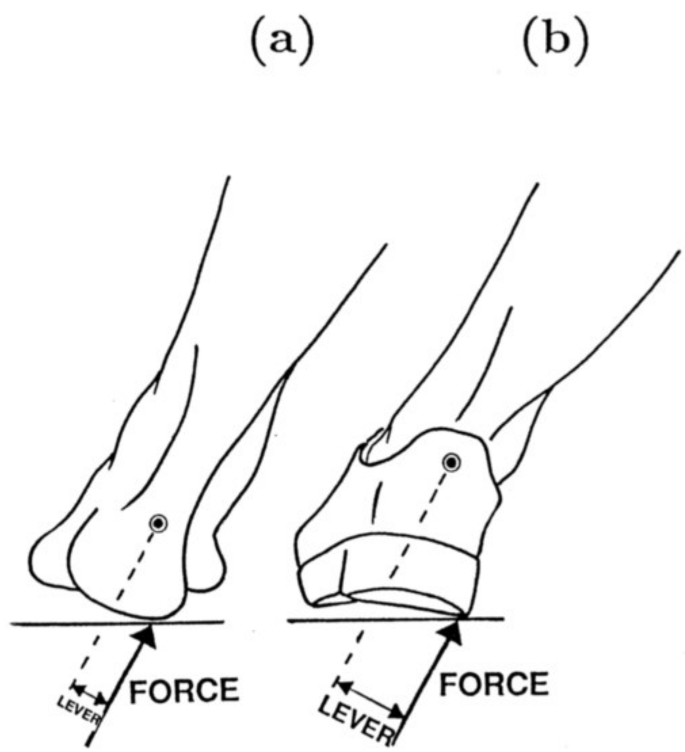

Figure 1—Sideward cutting movements (a) barefoot and (b) shod. Indicated are the possible levers between the ground reaction force and the estimated axis of the subtalar joint.

The peroneus muscles are the most important everters at the ankle. The reaction time of these muscles is between 60 ms and 90 ms, which is too long to actively prevent an ankle sprain (5,6,20,30). It has been shown that during lateral cutting movements inversion takes place within 30–50 ms after touchdown (16,25,28). It can be assumed that the reaction time of nonactivated ankle everters is insufficient to prevent ligament injuries.

Slipping seems also be a reason for injuries. It may occur between (i) the shoe and the surface and (ii) between the foot and the shoe. Point (i) has been studied by several investigators (7,12,19,28,31,32) and is of interest when the coefficient of friction is very low. This was not the case in the present study. Slipping inside the shoe, point (ii), has not been investigated intensively yet (16). The reason for this type of slipping may be due to high friction between the shoe and the surface. From a practical point of view it makes sense to postulate that slipping inside a shoe should be as small as possible.

Injury and Movement Statistics

Injury statistics are available for a number of sports activities where sideward cutting movements are part of the player's routine (Table 1). Ankle injuries account for between 15% and 30% of all reported injuries with ankle sprains being most frequent. In short, in a considerably high number of sporting activities, about every fifth injury occurs at the ankle.

Movement statistics can be used to point out the most frequent movements occurring in a given activity (4,12,25). They are based on video analyses where different movements of the players are counted in separate categories. With respect to ankle sprains cutting, stopping, landing and rotating can be considered to bear a higher risk of injury (25). When adding these "high risk movements," one arrives at a percentage that indicates how often a given activity is carried out under a higher risk of injury. Basketball is the activity with the most frequent high-risk movements (70%), followed by European handball (65%), volleyball (48%), soccer (47%), tennis (under pressure) (42%), and tennis (routine) (30%).

METHODS

Subjects

Twelve male subjects (average age 25 yr) gave written informed consent to participate in the study. They had performed numerous sideward cutting movements during their athletic careers, and were free of injury and pain on the test day.

Test Protocol

The subjects performed a sideward cutting movement barefoot and with all five shoes on a linoleum surface.

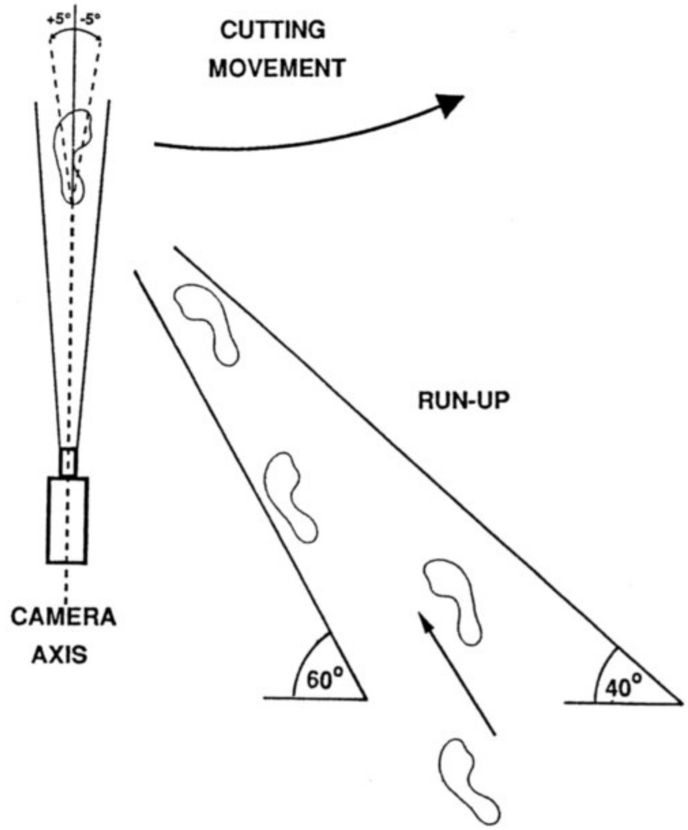

Figure 2—The set-up of the present study.

Similar to many sporting activities, they were allowed to use a forward and sideward run-up of four to six steps before performing the cutting movement; a task which was repeated by the subjects with ease (Fig. 2). Previous investigations used a run-up only in the lateral direction (10,12,16,19) which seemed to force a forefoot touch-down. However, to test the properties and the design of the rearfoot of a shoe sole, a forward and sideward run-up seems the better approach. All trials were visually controlled and were repeated when incorrect (i.e., footfall outside the film area; rearfoot rotated more than ± 5° away from the camera axis, no rearfoot contact with the ground).

All trials were filmed at 150 frames·s^{-1} and digitized from the last frame before ground contact of the foot to 60 ms after contact. As previously described this time period was long enough to cover the time during which injuries may occur. In addition to using test shoes, the subjects performed the cutting movement also barefooted. Previous studies have shown (16,25) that inversion decreased significantly in the barefoot condition, i.e., that a good lateral stability was achieved. In this investigation additional markers at the leg and foot were analyzed which should provide more insight into the barefoot kinematics.

Shoes

Five shoes of size 9 were included in the study (Fig. 3). Shoes 1 to 3 were commercially available court shoes

Figure 3—The test shoes used in this study.

with different shoe sole properties (Table 2). The shoes can be considered as extremes with respect to sole thickness, hardness, and torsional stiffness.

Shoe 4 was the first prototype with special rearfoot design: It consisted of a hollow inner core and a rubber bottom which allowed the two sidewalls to move laterally under a given load. In a pilot study, this prototype was tested statically under a given load of 2 times body weight and a leg angle of 25–30° (this can be expected in sideward cutting (10,16,25)). Under these conditions the sole began to deform as shown in Figure 4. The sole produced this behavior in both directions, i.e., in lateral as well as in medial direction. This may be regarded as an anisotropic property which seems important for various sports activities. The idea was to test whether during an actual cutting movement the sidewalls would deform such that the rearfoot would remain in a stable position, i.e., medially lower than laterally.

Shoe 5 was the second prototype with a special rearfoot design. It was used to test the assumption that when slipping of the foot inside the shoe is allowed it may improve the lateral stability. The shoe was provided with a noncompressible double inner sole where slipping can easily take place between the two surfaces (Fig. 5).

It has been shown (22–25) that the torsional stiffness of a shoe can vary considerably depending on the design and properties of the shoe soles. The torsional stiffness is the resistance of a material (shoe and/or foot) against torsion with respect to its longitudinal axis (22). A high torsional stiffness (i.e., a stiff shoe sole) leads to a small angle of torsion and *vice versa*. To test this property on the shoes a static testing machine (22,23) was used to apply a torque of 2 Nm about the longitudinal axis of the test shoes; a goniometer provided the amount of rotation at this given moment. Least torsional stiffness was measured with shoes 2 and 4, largest torsional stiffness was found with shoes 3 and 1; shoe 5 was found intermediate (Table 2).

TABLE 2. Description of the test shoes.

Shoe	Stiffness (Shore C)	Thickness (cm)	Construction	Type	Torsion (Degrees at 2 Nm)
1	53	2.9	High cut	Basketball	4
2	83	1.8	Low cut	Handball	15
3	85	2.7	Low cut	Cross-training	3
4	85	2.7	Low cut; sole with hollow core	Prototype	11
5	74	3.1	Low cut; double inner sole	Prototype	9

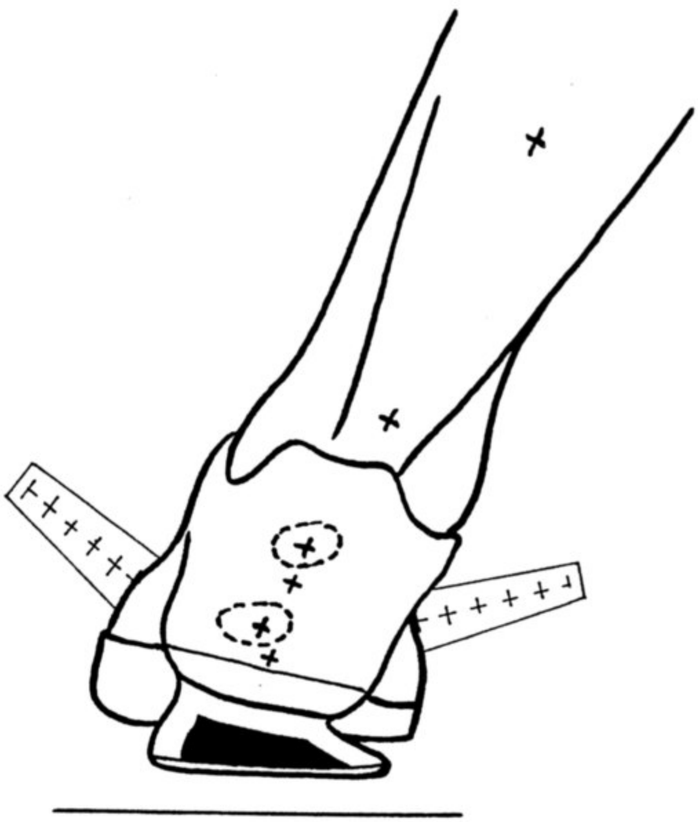

Figure 4—Shoe 4 of the study with the special sole design; shown is a cross-section through the shoe sole at the heel.

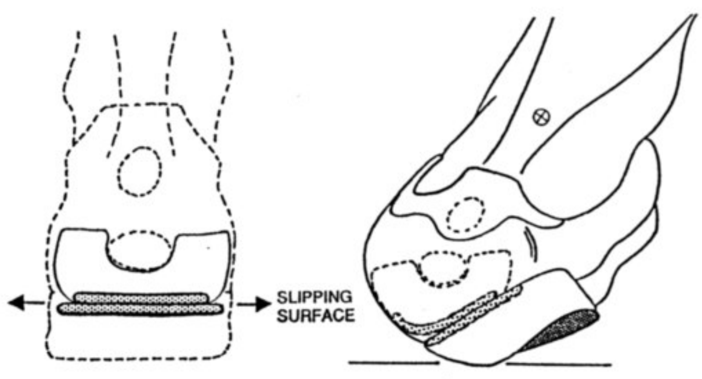

Figure 5—Shoe 5 of the study with a noncompressible double inner sole; (a) standing position and (b) position during slipping.

Markers and Film Analysis

A standard two-dimensional film analysis for lateral cutting movements was used as described earlier (10,12,25,28). Two windows were cut into the heel counters of the shoes to make the movement of the heel visible inside the shoe (16). The projection error was minimized by (a) using relative angles for the comparison of different shoes and (b) using a within subject test design. The digitizing error was determined by repeatedly digitizing the same trial; for 10 repetitions the SD for the angles of this study was less than $\pm$ 0.5°. The error due to skin marker movement could not be determined; further investigations need to clarify this issue. Generally, in sideward movements ankle inversion of the order of 20 degrees or more can be expected. In this respect, the possible errors due to projection and manual digitizing can be neglected.

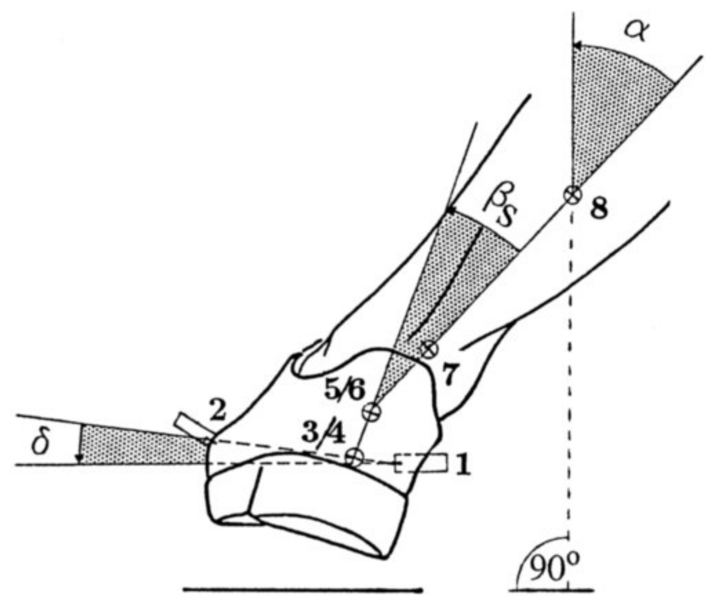

Figure 6—The position of markers an definition of angles used in this study.

Eight markers were used as shown in Figure 6; their positions have been previously described (16,24). The heel markers were set through the windows of the shoes onto the skin of the standing subjects. Two foam rubber sticks (0.5 g) were taped over the forefoot markers (nos. 1 and 2) at the location of the first and fifth metatarsal heads to facilitate the location of the two metatarsals during digitizing.

Definition of Angles and Parameters; Statistical Treatment of the Data

The markers used in the study allowed to describe the angular orientation of the leg (α), the rear of the shoe (γ), the heel inside the shoe, and the forefoot of the shoe (δ) (Fig. 6). Based on this information three relative angles

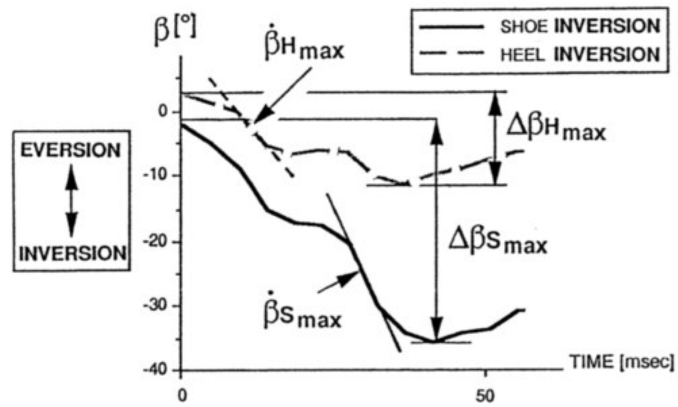

Figure 7—Definition of parameters used in this study.

were calculated for each individual curve (no smoothing): the Achilles tendon angle (leg vs rear of the shoe and leg vs heel inside the shoe) referred to as shoe-inversion and heel-inversion (β_S and β_H), and the torsion angle (forefoot vs rearfoot; $\theta = \delta - \gamma$). The difference between the shoe-inversion and the heel-inversion was defined as slipping.

According to injury mechanisms and movement statistics it is of particular interest to look at the maximal range of motion in inversion and the angular velocity of this movement. For this reason different parameters were defined which were used to check the various shoe conditions statistically. The definitions of the parameters for the shoes are (Fig. 7):

$\Delta\beta_{Smax}$: The maximal range of motion in inversion between the instant of touchdown and 60 ms.

$\dot{\beta}_{Smax}$: The maximal velocity in inversion between the instant of touchdown and 60 ms.

The respective parameters for the heel inside the shoe are: $\Delta\beta_{Hmax}$ and $\dot{\beta}_{Hmax}$. The parameters for the leg angle $\Delta\alpha_{max}$, the forefoot angle $\Delta\delta_{max}$ and the torsion angle $\Delta\theta_{max}$ were defined according to the maximal inversion angle ($\Delta\beta_{Smax}$) as the maximal range of motion between the instant of touchdown and 60 ms.

Previous investigations of the inversion in sideward cutting movements have shown a standard deviation of 5° and more (16,25,26), which is larger than in running (13,24). The intraindividual variability however, was for both activities about 50% of the interindividual variablity (24,26). Therefore, inversion in sideward cutting movements seems to vary quite largely between subjects, perhaps depending on the individual ankle joint integrity or on individual movement patterns. Consequently, a non-parametrical test for small dependent samples, the Wilcoxon test, was used.

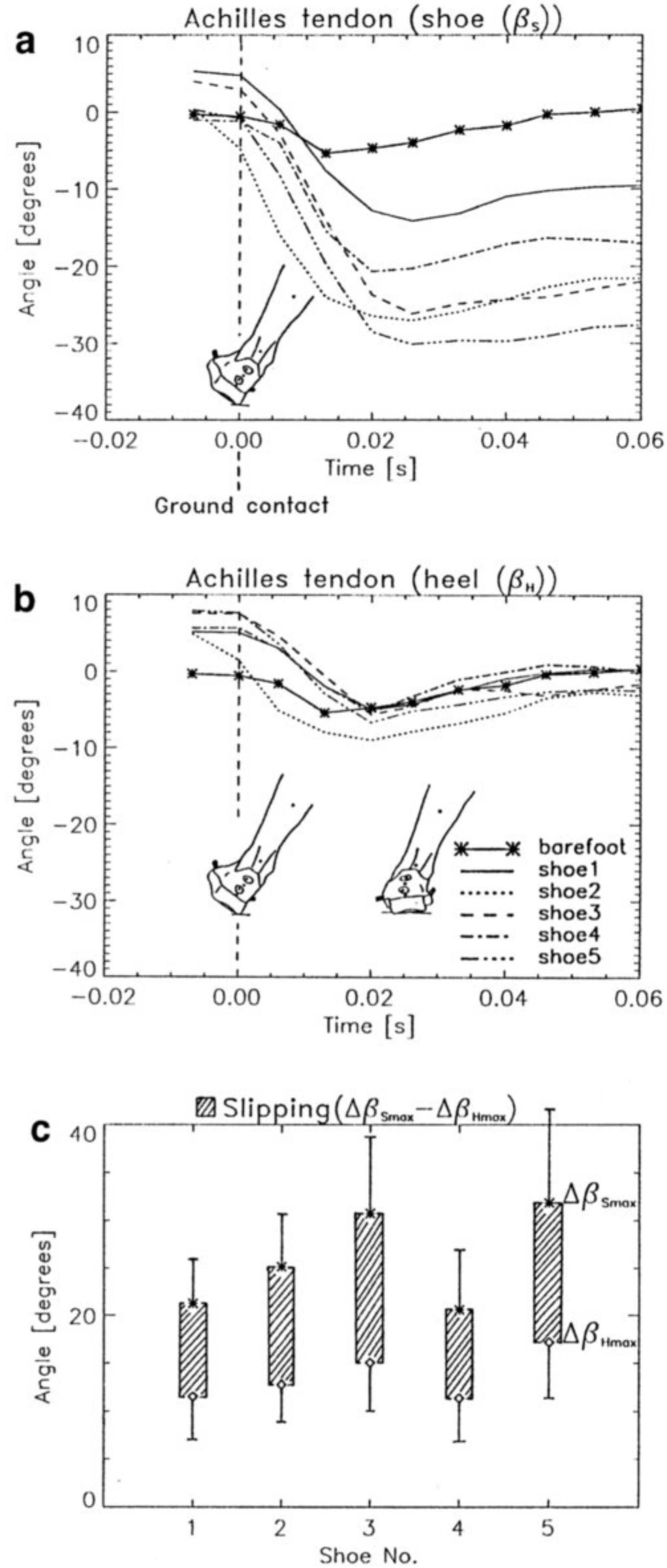

Figure 8—a) Shoe-inversion with five different shoes. For comparison the inversion of the barefoot condition is also shown (mean SD ± 5.4). b) Heel-inversion with five different shoes (mean SD ± 5.1). c) Averaged maximum values and SD of $\Delta\beta_{Smax}$ and $\Delta\beta_{Hmax}$. The differences between these two values represent the average slipping inside the test shoes.

RESULTS

Touchdown

The foot contacted the ground in either of the two variations: (a) rearfoot before forefoot in 77% of the trials and (b) forefoot before rearfoot in 23% of the trials. The time that elapsed between the forefoot and rearfoot touchdown (variation (b)) was between 10 and 30 ms, and the maximum inversion was reached before the last digitized frame. The movement of the rearfoot was similar for the two types of touchdowns. In other words the two variations of touchdown differed only with respect to the point in time where the rearfoot reached the ground. As a consequence, the two sets of data for touchdown variation (a) and (b) were pooled for further analyses. The average touchdown velocity barefooted and shod was of the same order of magnitude (barefoot: 1.23 ± 0.29 $m{\cdot}s^{-1}$, shoes: 1,29 ± 0.33 $m{\cdot}s^{-1}$).

Achilles Tendon Angle (Shoe-Inversion β_S)

There are large differences between the different test conditions: for the barefoot trials, the inversion movement is less than 10°, whereas with shoes it is more than 20° (Fig. 8a). This shows that shoes in general have an important influence on the rearfoot kinematics in sideward cutting movements.

The Achilles Tendon Angle (Heel-Inversion β_H) and Slipping ($\Delta\beta_{Smax}$-$\Delta\beta_{Hmax}$)

Heel-inversion was generally considerably less than shoe-inversion but more than in the barefoot tests (Fig. 8b). Before touchdown the heel was everted, which indicates that even during the flight phase the foot moves inside the shoe. Least slipping during ground contact occurred in shoes 1 and 4, most with shoes 3 and 5 (Fig. 8c).

Leg Angle (α), Forefoot Angle (δ), and Torsion Angle (θ)

The results for the leg, forefoot, and torsion angle were generally in agreement with previous studies investigating cutting movements (10,12,16,25). Among the various shoe conditions, no significant differences were found (Fig. 9a).

The forefoot angle (Fig. 9b) shows the most striking differences between the barefoot and the shod conditions. It seems that the landing technique in a sideward movement is depending on whether shoes are worn or not. With respect to torsion (Fig. 9c), the barefoot remained in position of around −20° within the time of interest which can be related to the reduced forefoot angle (Fig. 9b). Shoe 1 showed an average torsion angle of −10°, which can be related to the reduced rearfoot movement (Fig. 8a) and to the support provided by the high-cut upper. All other shoes had one result in common: torsion increased from touchdown to maximum, which, given similar forefoot angles (Fig. 9b), is equivalent to an inversion movement of the rearfoot relative to the forefoot. Such a movement is not welcomed to improve the lateral stability.

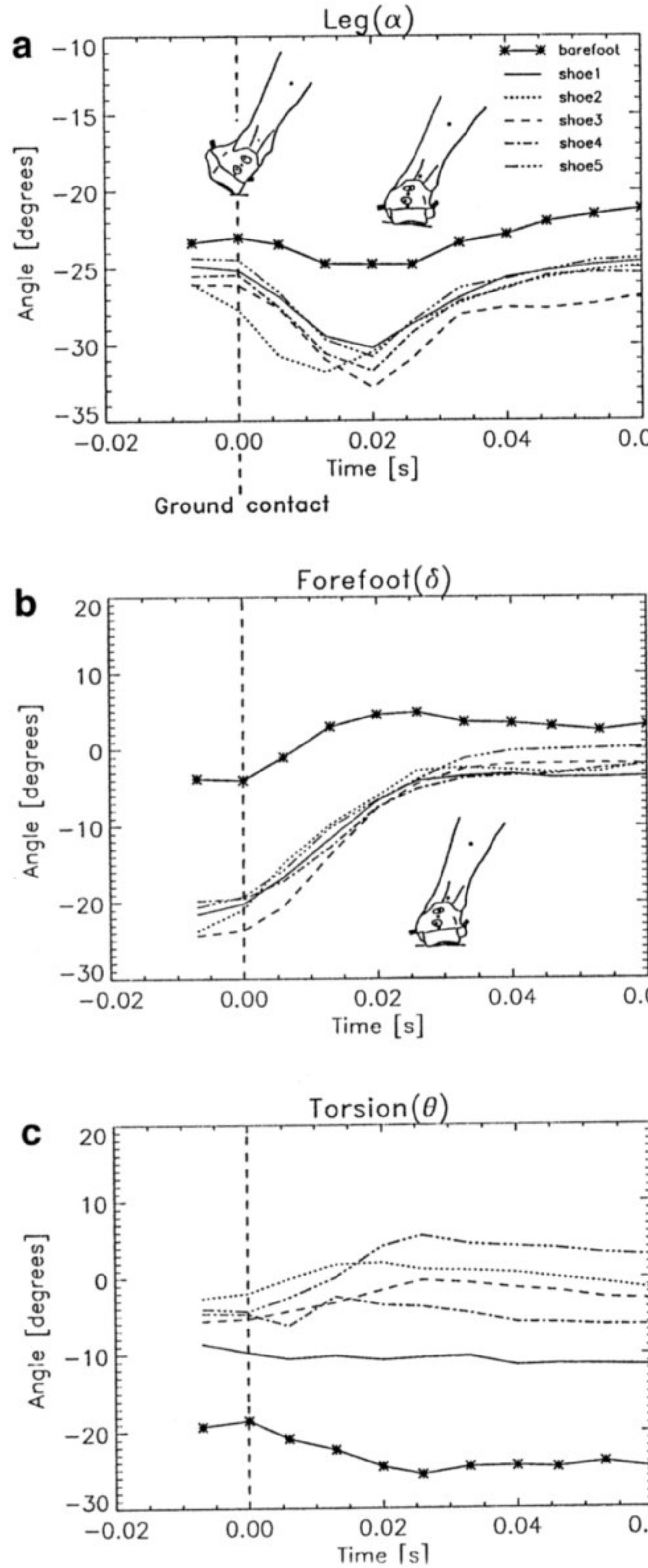

Figure 9—a) The leg angle with five different shoes (mean SD ± 4.7). b) The forefoot angle with five different shoes (mean SD ± 4.7). c) The torsion angle with five different shoes. For comparison the torsion of the barefoot condition is also shown (mean SD ± 4.2).

DISCUSSION

Shoe-inversion takes place within the first 40 ms after touchdown (Fig. 8a), which is faster than the latency of the peroneus muscles as previously described (5,6,20,30). Thus, to be effective, any device, aid, or construction that is designed to decrease the risk of injury should work

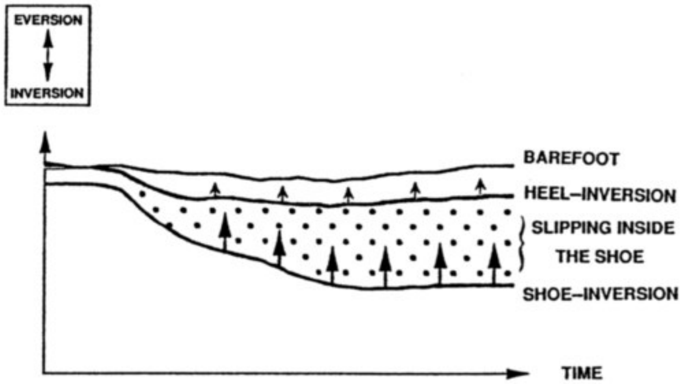

Figure 10—Considerations of how to improve the lateral stability of a sport shoe (the arrows indicate the direction of improvement).

immediately after touchdown. An improved lateral stability may be achieved by reducing inversion and slipping (inside the shoe), provided no further compensatory movements occur at other joints (Fig. 10).

Compensatory Movements

Leg (α) and forefoot (δ) angles were very similar for all five shoe conditions (Fig. 9, a and b; Tables 3 and 4). No significant differences were found between the shod conditions. In other words, different shoe sole designs and shoe sole properties did not provoke any compensatory movements at the forefoot and the leg.

The barefoot condition was clearly distinguished from all shod conditions with respect to the forefoot and the leg angle. Barefooted, immediately after touchdown, the leg remained almost constant (Fig. 9a) whereas with shoes the leg moved toward the ground within the first 20 ms after touchdown. After this short time period the leg reversed the direction. This can be understood in view of the overall movement of the subject's body which is still moving in a lateral direction at this point in time, thus raising the leg toward the vertical.

When looking at the forefoot (Fig. 9b), there are two different landing techniques that can be observed. Barefooted "the foot-flat approach" is chosen by lowering the metatarsals parallel to the ground. With shoes the medial border of the forefoot touches the ground first causing a forefoot angle of around 20°. Within a time span of 40 ms the forefoot is then lowered toward the ground hereby rolling over the medial border of the shoe sole. In other words, a "rolling approach" can be observed with shoes. Differences within the shod conditions were not found for the forefoot angle.

When testing the parameter of maximum torsion two different results were apparent. (i) Shoes 1, 2, and 4 were not significantly different from barefoot (Table 4). In other words, these shoes were not torsionally stiffer than the barefoot during the time of interest. This corresponds well to the results of the testing machine (Table 2) in which shoes 2 and 4 had the largest torsion angles. Shoe 1 was torsionally stiffer in the testing machine; however, the machine cannot take into account the effect of a high-cut shoe in which the upper may act as a lever to improve torsion. (ii) Shoes 3 and 5 were significantly different from barefoot, i.e., these shoes were torsionally stiffer than the barefoot. This relates also to the values of the testing machine, which were low for these two shoes, indicating a large torsional stiffness. Also, shoes 3 and 5 have a large sole thickness and a relatively hard sole. These shoe sole properties seem to have a negative effect on torsion. This may also be the reason for the significant differences of shoe 5 relative to shoe 2 and 4. Shoe 4 differed significantly from shoe 3 during the cutting movement, which is again in agreement with the results of the testing machine.

In summary, it may be concluded that in a sideward cutting movement with shoes the properties of the shoe sole (rearfoot design, hardness, thickness, torsional stiffness) influence mainly the kinematics of the foot, but not of the leg. The comparison of barefoot versus shod results reveals differences at the leg, rearfoot, and forefoot.

Reduction of Inversion

Inversion is mostly reduced in the barefoot condition. Compared with all shoe conditions (Table 5), the differences are significant, except for shoe 1 in the angular velocity. The major reason for this reduction seems to lie in the shoe sole, which provides a leverage to invert the foot, which decreases the lateral stability. However, the results show that the lateral stability can be improved with an appropriate shoe sole design. The advantages in shoe 1 seem to be the soft shoe sole material and the high-cut upper; the advantage in shoe 4 its new shoe sole design, which showed improvement even with a low-cut upper. Further investigations should include kinetic measurements to show how the moments about the subtalar joint are effected by this new shoe sole design.

Shoes 3 and 5 showed the worst results with respect to lateral stability. Either the range of motion or the angular velocities were high. Both of these shoes have a hard and thick shoe sole. Again this is an indication, that the shoe sole may act as a lever about the subtalar joint axis. Shoe 2 showed intermediate results; statistically it could not be clearly separated from the shoes with a better nor from the shoes with a worse lateral stability.

Reduction of Slipping

The movement of the heel inside the shoe (slipping) was least in shoes 1 and 4 (Fig. 8c). This is also reflected in the statistics (Table 6), where the range of motion of the barefoot condition was not different from these two shoes but from all other shoes. Shoe 2 placed between the extremes. Most slipping occurred in shoes 3 and 5. This shows that slipping may be provoked, given certain materials for the shoe construction are used. On the basis of these results, a shoe design that allows slipping inside the shoe cannot be recommended.

TABLE 3. Means and SD of the test parameters.

Parameter	Barefoot	Shoe 1	2	3	4	5
$\Delta\beta_{Smax}$	9.2 ± 5.8	21.3 ± 4.4	25.2 ± 5.6	30.8 ± 8.0	20.6 ± 6.0	31.9 ± 9.4
$\Delta\beta_{Hmax}$	9.1 ± 5.8	11.6 ± 4.0	12.8 ± 3.6	15.1 ± 4.6	11.4 ± 4.2	17.2 ± 5.3
$\dot{\beta}_{Smax}$	1002 ± 631	1328 ± 448	2014 ± 938	1844 ± 581	1829 ± 661	1980 ± 715
$\dot{\beta}_{Hmax}$	1006 ± 619	870 ± 355	1212 ± 629	1193 ± 495	928 ± 333	1234 ± 471
$\Delta\alpha_{max}$	5.4 ± 2.9	6.0 ± 2.7	5.2 ± 2.9	7.3 ± 3.8	6.6 ± 2.6	7.0 ± 3.7
$\Delta\delta_{max}$	10.0 ± 7.1	18.2 ± 4.8	19.9 ± 6.1	22.6 ± 6.2	17.9 ± 5.5	20.3 ± 8.0
$\Delta\theta_{max}$	10.0 ± 6.6	6.0 ± 4.3	5.8 ± 2.9	3.6 ± 2.6	7.0 ± 3.4	3.1 ± 1.8

TABLE 4. Statistics of the test parameters $\Delta\delta_{max}$ and $\Delta\theta_{max}$.

$\Delta\theta_{max}$	$\Delta\delta_{max}$ Barefoot	Shoe 1	2	3	4	5
Barefoot		$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$
Shoe 1	NS		NS	NS	NS	NS
2	NS	NS		NS	NS	NS
3	$P < 0.01$	NS	NS		NS	NS
4	NS	NS	NS	$P < 0.01$		NS
5	$P < 0.01$	NS	$P < 0.05$	NS	$P < 0.01$	

TABLE 5. Statistics of the Test Parameters $\Delta\beta_{Smax}$ and $\dot{\beta}_{Smax}$.

$\dot{\beta}_{Smax}$	$\Delta\beta_{Smax}$ Barefoot	Shoe 1	2	3	4	5
Barefoot		$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$
Shoe 1	NS		NS	$P < 0.01$	NS	$P < 0.01$
2	$P < 0.01$	$P < 0.05$		NS	NS	NS
3	$P < 0.01$	$P < 0.05$	NS		$P < 0.01$	NS
4	$P < 0.01$	NS	NS	NS		$P < 0.01$
5	$P < 0.01$	$P < 0.05$	NS	NS	NS	

TABLE 6. Statistics of the test parameters $\Delta\beta_{Hmax}$ and $\dot{\beta}_{Hmax}$.

$\dot{\beta}_{Hmax}$	$\Delta\beta_{Hmax}$ Barefoot	Shoe 1	2	3	4	5
Barefoot		NS	$P < 0.05$	$P < 0.01$	NS	$P < 0.01$
Shoe 1	NS		NS	NS	NS	$P < 0.01$
2	NS	NS		NS	NS	$P < 0.05$
3	NS	NS	NS		NS	NS
4	NS	NS	NS	NS		$P < 0.01$
5	NS	$P < 0.05$	NS	NS	NS	

The angular velocity of the heel inside the shoe did not show (with one exception) any significant differences. As shown previously (16,24) the angular velocities inside a shoe are generally lower than those of the shoe itself. This leads to the conclusion that the foot may be protected inside the shoe.

Cutting movements often occur in the lateral direction, but they may also occur in the medial direction. Therefore, a preferable improvement of the stability should work for both sides. A possible solution could be an anisotropic behavior of the shoe sole material which would improve the stability in the lateral as well as the medial direction (26).

In summary, the stability of shoes used for sideward cutting movements can be improved due to changes of the material properties and design that are effective immediately after touchdown. Further research is needed to formulate the requirements of such shoes after the touchdown phase (the midstance and take-off) as is already the case for running shoes (13).

Conclusions

Several conclusions can be drawn from this investigation:

- To decrease the risk of injury in lateral cutting movements, shoes or external devices must reduce inversion of the shoe and the foot inside the shoe (Fig. 10) immediately after touchdown within the first 40 ms of the stance phase.
- The best lateral stability can be observed in the barefoot condition.

• Shoe sole properties influence the lateral stability at the ankle during sideward cutting movements, but they do not provoke compensatory movements at the forefoot and the leg. The stability seems to be dependent on the hardness, thickness, and torsional stiffness of the shoe sole by increasing or reducing the leverage about the subtalar joint (see also ref. 21). The lateral stability can be further improved by the upper of a shoe (high-cut shoes decrease supination more than low-cut shoes).

• Shoe sole designs may be developed that allow a deformation on the medial side, thereby building a ramp, and thus improving the lateral stability. A future shoe sole design should also include anisotropic properties for good stability in the lateral as well as the medial direction.

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