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Clinical Biomechanics of Skiing

SUMMARY

Abnormalities of lower-leg alignment may lead to a number of skiing problems. Tibia vara may cause difficulties in turning and riding a flat ski unless the boot cuff is properly adjusted to the lower leg. Varus deformities in the foot may lead to boot-fitting difficulties, foot and knee pain, and the inability to edge a ski turn properly. Compensation for these problems with an appropriately posted, corrective, orthotic device may allow skiing participation with greater comfort and better performance. (*Can Fam Physician* 1988; 34:107–114.)

RÉSUMÉ

Les anomalies d'alignement du tiers inférieur de la jambe sont susceptibles d'amener un certain nombre de problèmes à la pratique du ski. Un tibia en varium engendre des difficultés à tourner et à skier à plat sauf si on ajuste correctement la jambière de la botte à la partie inférieure de la jambe. Les malformations en varus au niveau du pied rendent difficile l'adjustement des bottes, provoquent des douleurs au niveau du pied et du genou et entravent la capacité de tourner adéquatement. Une orthèse correctrice appropriée et bien ajustée compensera ces problèmes, améliorera les performances et permettra de skier tout en étant plus confortable.

Key words: sports medicine, skiing

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CANADA provides ideal conditions for winter sports, and it is estimated that over 2 million Canadians participate in alpine skiing on a regular basis.[1] With 4 million feet locked into tightly fitting ski boots for hours on end, it is not surprising that physicians are frequently consulted about painful feet resulting from skiing. Many of these problems are caused simply by poorly fitted boots. Some individuals, however, are particularly prone to painful feet and knees, as well as to difficulties with their ski technique, because of abnormalities in the biomechanics and alignment of their feet and lower legs.

It is recognized that lower-leg alignment is an important factor in skier comfort, safety, and performance.[2–4] Recent advances in ski-boot technology now provide adjustment for individual variations in lower-leg alignment. When these newer boots are properly selected, fitted, and coupled with an appropriate corrective orthotic device, they enable skiers to perform better without sacrificing comfort. Strong, technically demanding skiers who suffer no discomfort may also benefit from correction of their biomechanical alignment so as to optimize their skiing performance.

It is important to understand the mechanics of how and why a ski turns in order to appreciate the significance of the leg-boot-ski interface and the ways in which abnormal biomechanics can affect this relationship. Skiing technique is continuously updated by the Canadian Ski Coaches Federation and the Canadian Ski Instructors Alliance, and their manuals are excellent in-depth sources of technical information.[5, 6]

Relevant Aspects of Skiing Technique

Skiing is a series of linked turns that function to control the rate of descent and direction of travel down a slope. A carved ski turn has three essential components: pivoting (turning), edging, and pressuring the ski; the turning occurs primarily on the inside (up-hill) edge of the ski on the downhill foot.

A ski is constructed with a natural bend (termed 'camber') so that when it is unweighted and laid flat, the tips and tails are in contact with the snow, and the mid portion is 1 cm-2 cm off the snow. Pressure applied to the centre of the ski will be transmitted along its length, deforming the ski, reversing its camber, and allowing it to stay in contact with the snow. When the pressure is released, the ski will return to its normal shape and release the stored energy.

Skis are also constructed so that the running surface is wider at the tips and tails than it is in the middle; the difference in width is termed 'side-cut'. This feature creates a natural curve when the ski is placed on its edge and its camber is reversed by the application of pressure. Each ski has its own natural turning radius, depending on the degree of side-cut: a narrower side-cut is designed for a shorter turning radius. The shape and radius of any given turn is thus determined by the ski's natural turning characteristics, the edge angle, and the amount of pressure applied. A greater edge angle and higher pressure result in a shorter-radius turn.

Linking ski turns together depends on edging, pressuring and turning the skis back and forth across the fall line. The skis are pivoted into the new direction of travel by 'unweighting', which reduces the pressure applied to the tips and tails. This is accomplished by moving the body forward and upward, and these movements are assisted by the release of the energy stored in the ski through the reversal of its camber.

Figure 1
Counter-rotation

The skier's legs and skis are pointing across the hill while her upper body is facing down the hill in anticipation of the next turn.

Following unweighting and pivoting, edging serves to control the skis' speed and direction of travel. The amount of edging required is determined by the skier's speed, the steepness of the slope, and the radius of the turn. Edging is initiated by eversion of the ankle, and greater degrees of edging are accomplished by progressive knee and hip flexion, and valgus positioning of the knee. While the legs are initiating and maintaining the turn across the fall line, the upper body is acting in an independent fashion and faces more directly downhill. This separation of upper and lower body masses is termed 'counter-rotation', since, in the transverse plane, the skis have been turned to a greater degree than the upper body (Figure 1). At the end of the turn, considerable stored energy is available for initiating the next turn, as a result of the pressure built up during edging and the 'corkscrew' effect of counter-rotation.

Throughout the turn, the most desirable body position is one that actively resists forces applied to the ski by the snow, yet maintains the center of gravity over the skis. Although simply leaning or banking into the hill will provide resistance to the turning forces, this position shifts the body's centre of gravity up the hill and away from the skis, which can predispose to side-slipping or falling up-hill, especially on steep or icy terrain. The optimum body position, known as 'angulation', is characterized by varying degrees of ankle eversion and dorsiflexion, flexion of the knee and hip, and lateral bending at the waist with torso counter-rotation so that the body weight is maintained over the downhill ski (Figure 2). The degree of angular movement at each joint and the amount of counter-rotation required during the turn are directly proportional to the steepeness of the slope, the speed of the skier, and the desired radius of the next turn.

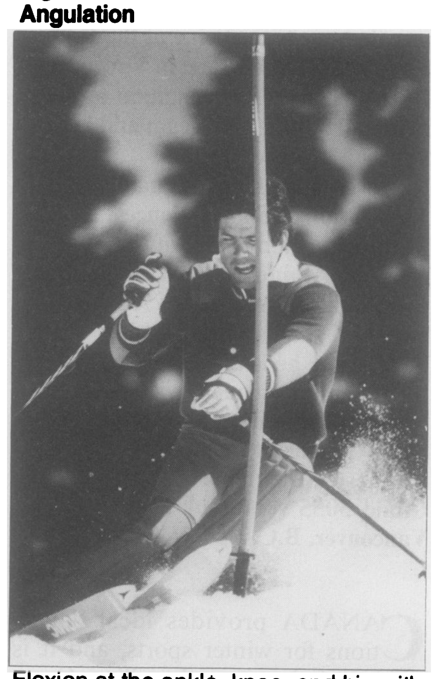
Although edging technique can be improved with training, the alignment of the bones of the lower leg and feet determines the ease with which edging can be accomplished. For some skiers, biomechanical abnormalities can limit technical abilities and provide a barrier to improvement.

Optimum alignment of the knee and lower leg occurs when the tibia is in line with the rearfoot and forefoot, and perpendicular to the snow (Figure 3), thus allowing the ski to ride flat, without alteration of the skier's body position. The most common deformities are of the varus type, which arise when the leg or foot is angled towards the midline. The effects of excessive tibia varum are apparent in the static, weight-bearing stance and are transmitted passively through the boot cuff to the ski-snow interface. Conversely, problems caused by varus alignment of the rearfoot and forefoot are often dynamic in nature and may only become functionally apparent during skiing. Since tibia varum differs from varus deformities of the feet both in the clinical and technical presentation and also in the proper method of correction, the two conditions will be discussed separately. It should be remembered, however, that the two problems are interdependent and must both be addressed and corrected for optimum skiing.

Lower Leg Varus: Problems and Correction

Since the ski boot functions as a rigid extension of the lower leg, uncompen-

Figure 2
Angulation



Flexion at the ankle, knee, and hip with lateral bending and counter-rotation at the waist to maintain the skier's centre of gravity over the downhill ski.

sated varus deformities of the tibia (Figure 4) are transmitted directly to the ski-snow interface and predispose the skier to ride on the outside edge of the ski (Figure 5). The skier will thus have difficulty initiating a parallel turn because of locked outside edges and will be forced to "pendulum" the legs or to "hop" or "stem" to unlock the outside edge. Uncompensated tibia vara also makes riding a flat ski difficult, especially in a tuck position. It can also force the skier to assume a wide-tracked stance, with the knees rolled outwards, or predispose to falling as a result of catching the outside edges.

Most of the modern, high-performance boots offer a boot-cuff adjustment to accommodate varying degrees of tibia vara and allow the skier to ride a flat ski (Figure 6). Non-adjustable boots have a pre-set angle designed for the average skier, and consequently are unable to accommodate the extremes of individual anatomical variations. On average, men have a greater degree of tibia vara than women, and the cuff angle on men's boots is designed to accommodate this difference. Women who wear men's boots may be overcorrected so that the greater degree of cuff canting forces the female skier to apply excessive pressure to the inside edge of the ski. This problem may also arise when the skier or boot fitter inappropriately uses the cuff-canting adjustment to assist the skier's "getting onto" the inside edge. Plastic cants placed between the boot and the ski were once commonly used, but they are cumbersome, expensive, non-adjustable, may interfere with normal binding function, and make changing to a different pair of skis very difficult. With the boots currently available, cants are required only in exceptional circumstances such as an excessive degree of tibia vara or to correct a significant leg-length discrepancy.

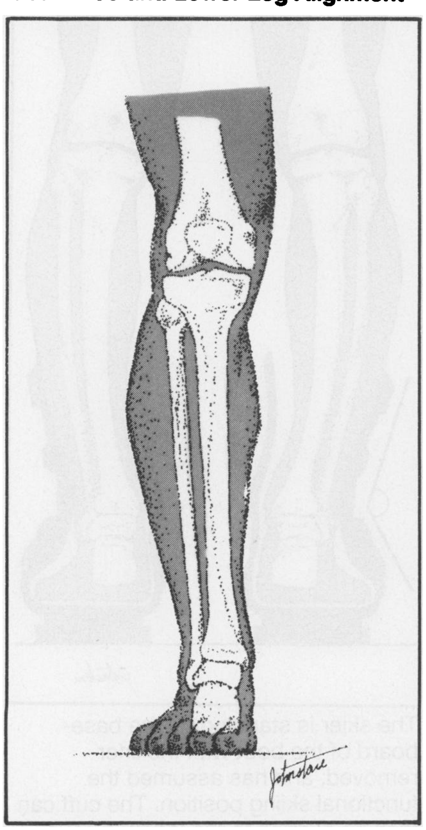
When correcting tibia vara, it is essential to align the boot cuff to the skier's leg in his or her normal skiing posture, with the feet apart, knees and hips flexed, and ankles dorsiflexed. Many skiers appear to have a high degree of tibial varum when standing with their feet together, but have little or none in their normal skiing stance, and inappropriate correction might lead to the problems previously discussed.

The simplest way of aligning the boot cuff is as follows. The skier stands on his footbeds on the base board of the shell with the liner removed and assumes a normal skiing posture, with knees slightly flexed and feet parallel and shoulder width apart (Figure 7). The boot cuff is then aligned so that it is parallel to the long axis of the lower leg (Figure 8). Alternatively, many ski shops have canting benches which allow the technician to level the boot sole while the wearer is in the skiing posture and thus adjust the cuff accordingly.

Varus Alignment of the Foot: Problems

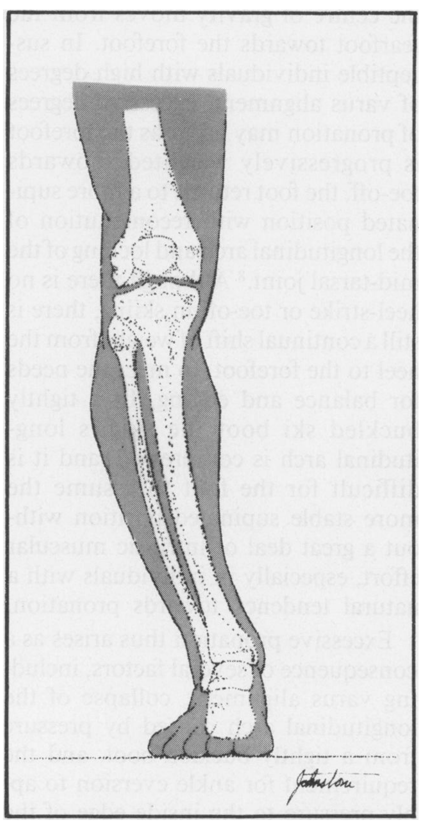
In contrast to tibia vara, alignment abnormalities of the heel and foot may

Figure 3
Ideal Knee and Lower Leg Alignment



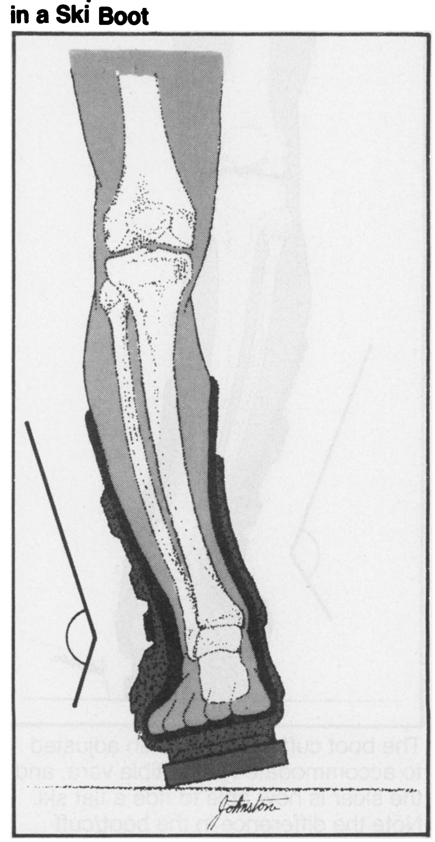
The tibia is vertical, and the subtalar joint and forefoot are in neutral alignment. Note that the midpoint of the patella is directly above the junction of the first and second toes.

Figure 4
Tibia Vara



The tibia is angled towards the midline. The upper limit of normal is 8°.

Figure 5
Uncompensated Tibia Vara in a Ski Boot



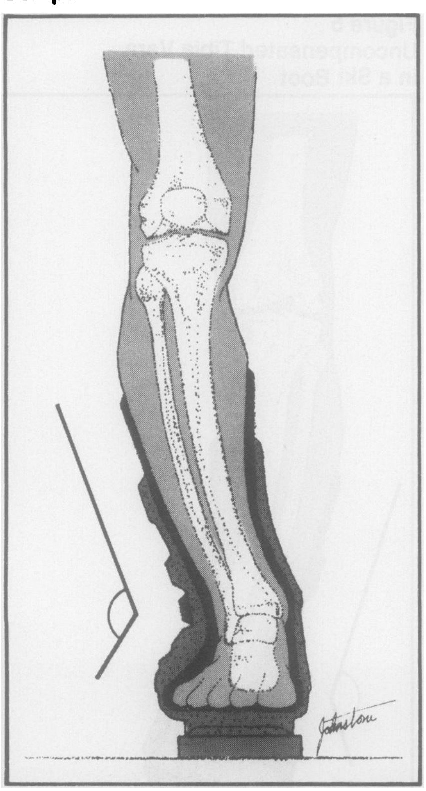
The boot cuff does not compensate adequately for the tibia vara, predisposing the skier to ride on the outside ski edge.

not be apparent when the skier is in a stationary position and may only be apparent during skiing, when the skier suffers from foot or knee pain or from problems with technique.

In an ideal foot, the forefoot and rearfoot are perfectly aligned and perpendicular to the long axis of the tibia (See Figure 3). Varus alignment in the non-weight-bearing position is present when the medial border of the foot is raised at the heel (subtalar varus) or at the metatarsal heads (forefoot varus) (Figure 9). During weight bearing, a varus-aligned foot will assume a pronated position, which is characterized by ankle eversion, abduction, and dorsiflexion.[7] Some authors refer to this weight-bearing position as "standing heel valgus", but it arises as a result of non-weight-bearing heel varus. The tendency towards pronation may be accentuated in individuals with a high degree of tibia vara.

Pronation at the subtalar joint is accompanied by obligatory internal rotation of the tibia at the knee (Figure 10).[8] When the alignment is near neutral, the amount of pronation is minimal, as is the degree of tibial rotation. Greater degrees of tibial, rearfoot and forefoot varus will result in relatively greater pronation and, consequently, in more internal tibial rotation.[7, 8]

Figure 6
Compensated Tibia Vara



The boot cuff has now been adjusted to accommodate for the tibia vara, and the skier is now able to ride a flat ski. Note the difference in the boot/cuff angles as illustrated in Figures 5 and 6.

The problem of excessive pronation is compounded when the varus-aligned foot is locked within a tightly buckled ski boot, with resultant flattening of the foot's longitudinal arch. This effect may not be recognized in the neutral standing position, but as the skier assumes the functional skiing posture, the centre of gravity shifts forward over the metatarsal heads, and the problem of excessive pronation becomes apparent. The weight shift towards the ball of the foot is necessary in order to apply pressure evenly to the ski tips and tails. The pressure applied to the forefoot is increased during unweighting, when the skier shifts his centre of gravity forward as he extends upward and forward. The forward weight transfer is somewhat analagous to the events of the normal gait cycle, in which pronation naturally occurs as the centre of gravity moves from the rearfoot towards the forefoot. In susceptible individuals with high degrees of varus alignment, excessive degrees of pronation may occur as the forefoot is progressively weighted. Towards toe-off, the foot returns to a more supinated position with reconstitution of the longitudinal arch and locking of the mid-tarsal joint.[8] Although there is no heel-strike or toe-off in skiing, there is still a continual shift of weight from the heel to the forefoot, to meet the needs for balance and edging. In a tightly buckled ski boot the skier's longitudinal arch is compressed, and it is difficult for the foot to assume the more stable supinated position without a great deal of intrinsic muscular effort, especially in individuals with a natural tendency towards pronation.

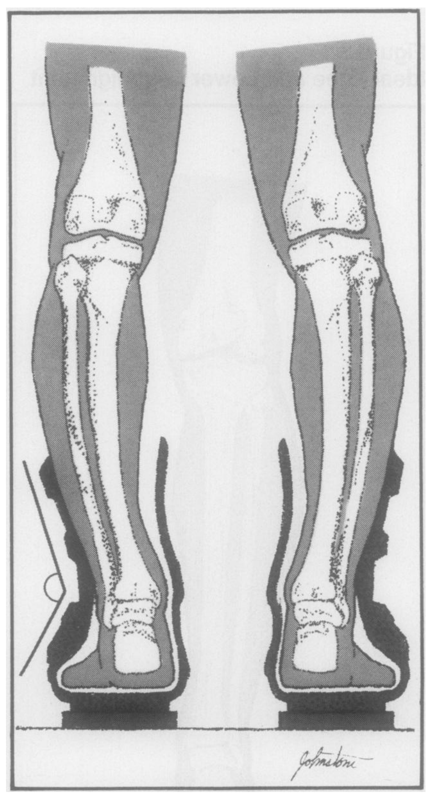
Excessive pronation thus arises as a consequence of several factors, including varus alignment, collapse of the longitudinal arch caused by pressure from a tightly buckled boot, and the requirement for ankle eversion to apply pressure to the inside edge of the ski.

The problems resulting from pronation arise when the skier is unable to compensate adequately for pronation and tibial rotation, and is forced to roll his knee medially to an extreme degree in order to edge the ski. The effect of varus alignment can best be understood by the use of an analogy in which the knee and lower leg are pictured as a lever arm attached to the foot in its unweighted position. It is apparent that the greater the degree of varus, the further the knee will have to be directed medially before pressure can be applied to the medial aspect of the foot (Figures 11A, 11B).

Excess pronation results in two types of problems: difficulties with ski technique, and foot and knee pain or injury resulting from attempts to compensate for the pronation. Not all skiers with excessive pronation have problems, and there are many top-level racers who have learned to compensate for their pronation through the use of extreme medial knee positioning while maintaining a proper skiing stance.

Technical problems arise when the

Figure 7
Tibia Vara: Measurement

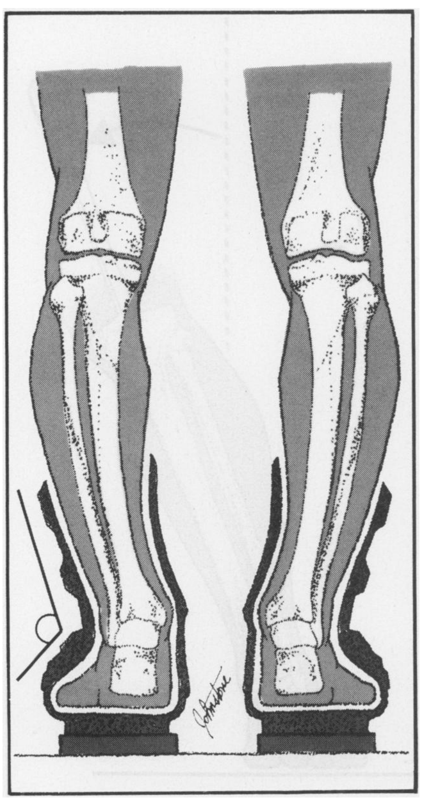


The skier is standing on the baseboard of the boot with the liner removed, and has assumed the functional skiing position. The cuff can then be aligned to the longitudinal axis of the lower leg. Note that if the skier uses a footbed or corrective orthotic, the device must be placed on the baseboard of the boot before correction.

skier is unable to position the knee with enough valgus to edge the ski adequately. Excessive tibial rotation and rolling of the knee can cause the hip and upper body to rotate into the hill, effectively preventing counter-rotation, angulation, and stabilization of the upper-body mass. The result is a turn characterized by side-slipping instead of edging; washing out of the tail of the skis because of unequal tip-to-tail weight distribution; banked turns, in which the skier leans into the hill; and excessive isotonic muscular contraction (Figure 12). Individuals with these technical problems often have little difficulty on gentle slopes with soft snow, but have more difficulty on steep, hard-packed or icy terrain.

The measurement of varus alignment in the static non-weight-bearing position has been described previously.[8, 9] It is also important to check for varus alignment while the skier is in the functional skiing position, with feet apart and hips and knees slightly flexed. If a vertical line from the midpoint of the patella falls medial to the junction between the first and second toes (see Figure 10), the skier has functional pronation. It is not uncommon for this axis to fall several centimetres medial to the great toe in persons with a high degree of functional pronation. Although static measurements will identify most individuals with excessive forefoot varus, this functional test will also detect the individual with a Morton's foot or a similar functionally hypermobile forefoot, even in the absence of a high degree of measurable varus. Many persons will have some degree of asymmetry on their functional pronation test, and they almost invariably identify the foot with the least amount of pronation as their best foot for turning and stopping.

Figure 8
Tibia Vara: Correction



The boot cuff has now been aligned to the axis of the lower leg so that the space between the leg and the medial and lateral aspects of the cuff are equal. Note the difference in boot/cuff angles as illustrated in Figures 7 and 8.

Varus Alignment of the Foot: Clinical Presentation

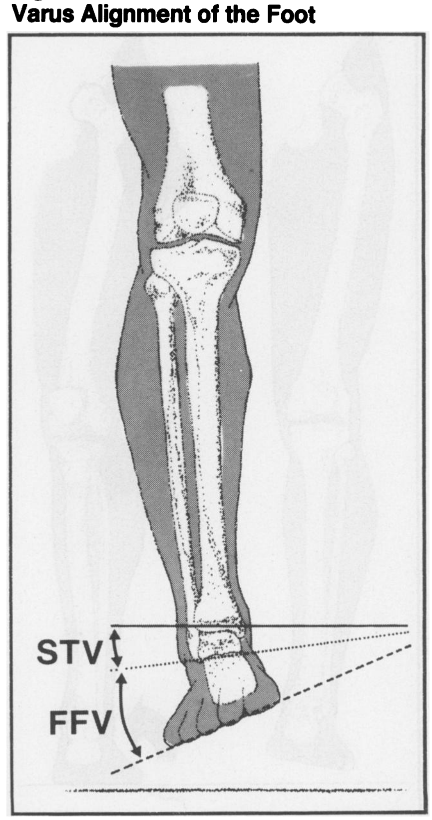
Individuals with excessive pronation have a characteristic clinical presentation resulting from attempts to stabilize their feet within their ski boots, or from the repetitive application of abnormal valgus stresses on their feet and knees.

Cold, painful feet are among the most common factors in discouraging would-be skiers from regular participation.[2, 10] Excessive pronation requires additional effort by the intrinsic and extrinsic muscles of the foot in order to stabilize the subtalar joint. Skiers who pronate excessively often curl their toes in an attempt to support their arch and reduce the degree of medial rotation of the knee necessary to maintain edging. This action can lead to painful, disabling cramping of the feet, which is often more apparent in conditions requiring greater edge control as when the skier is skiing aggressively in moguls or on ice. Tonic contraction of the tibialis anterior muscle causes its tendon to become more prominent, and this condition leads to local pressure, pain, and boot-fitting difficulties. This problem may be especially apparent in a rear-entry boot, in which the heel is held down by a relatively narrow band across the anterior aspect of the midfoot.

Skiers who have difficulty edging and turning will often attempt to stabilize their feet inside the boot by tightening the buckles excessively. This tactic does little to solve the problem of pronation and may, in fact, further compress the skier's longitudinal arch. Over-tightened boots may lead to impaired circulation, cold feet, paresthesia, and cramping. Excessive pronation can also lead to boot-fitting problems such as pressure points or bunions over the lateral heel and medial midfoot. These pressure points will not respond to simple modifications of the boot shell or liner, since the problem of excessive motion has not been remedied. Boot expansion by itself only provides more room for further pronation, increased foot motion, and continued pressure. Solving the problem of pronation depends on stabilizing the foot within the boot through the use of a corrective orthotic device[11, 12] and only then proceeding with shell modifications to accommodate bony or soft-tissue prominences.

The excessive internal rotation and valgus stress at the knee required to edge effectively can lead to abnormal

Figure 9
Varus Alignment of the Foot



Sub-talar (rearfoot) varus (STV: dotted line) and forefoot varus (FFV: broken line). Note how the sub-talar joint and forefoot are both angled towards the midline in the *unweighted* position.

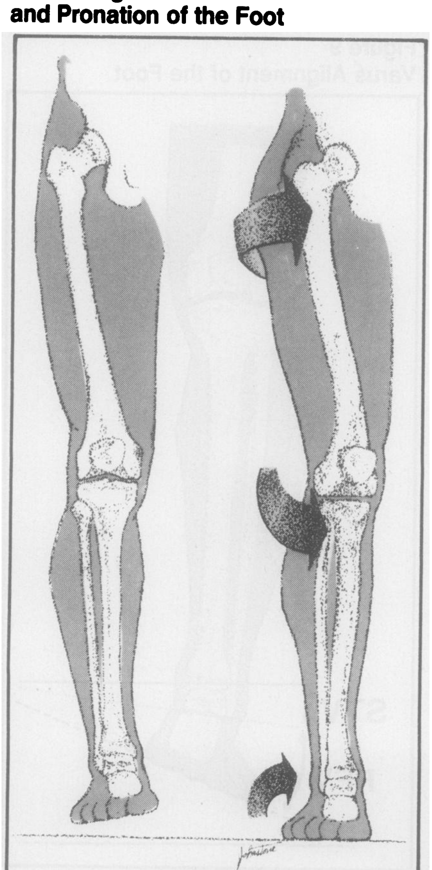
patellar tracking and painful knees; patellofemoral pain is a common result in skiers.[13] It is also possible that excessive valgus knee drive will predispose the skier to injuries of the medial collateral ligament in falls, as the result of a pre-loading effect. Maintaining the tibia in the position of internal rotation on the femur requires high tension on the pes anserinus tendons, which may lead to tendonitis at their insertion on the inferior medial aspect of the tibial plateau. In pes anserinus tendonitis, the presenting complaints may be misdiagnosed as meniscal tears or medial collateral ligament sprains. The biceps femoris is stretched, as it helps to stabilize the knee in the position of maximal internal rotation. Tendonitis at its insertion on the proximal fibula is a common problem in élite skiers, especially those competing in the slalom and giant slalom events.

Varus Alignment of the Foot: Solutions

Compensation for lower-extremity varus alignment is accomplished by stabilizing the sub-talar and mid-tarsal joints through the provision of sufficient support under the heel, arch and forefoot. If the lever analogy used above to explain the effect of pronation is again employed, it becomes clear that the addition of a wedge under the medial aspect of the foot will reduce the amount of valgus movement required to exert pressure on the medial border of the foot (Figures 13A, 13B). Therefore, in the ski boot, correction of pronation is provided through supporting the medial aspect of the foot. This may be accomplished through the addition of a medial wedge to existing ski-foot beds or through casting for a full-length, semi-rigid, corrective orthotic device with both forefoot and rearfoot posting as required (Figure 14). In a running orthotic, only partial correction of varus alignment is possible, but the rigid ski boot provides enough stability to allow correction of almost all of the measured forefoot and rearfoot varus. The key to proper foot control in skiing is adequate forefoot support; thus orthotics extending to the metatarsal heads are often inappropriate, since it is difficult to provide sufficient forefoot posting without creating an uncomfortable step-off at the front of the orthotic.

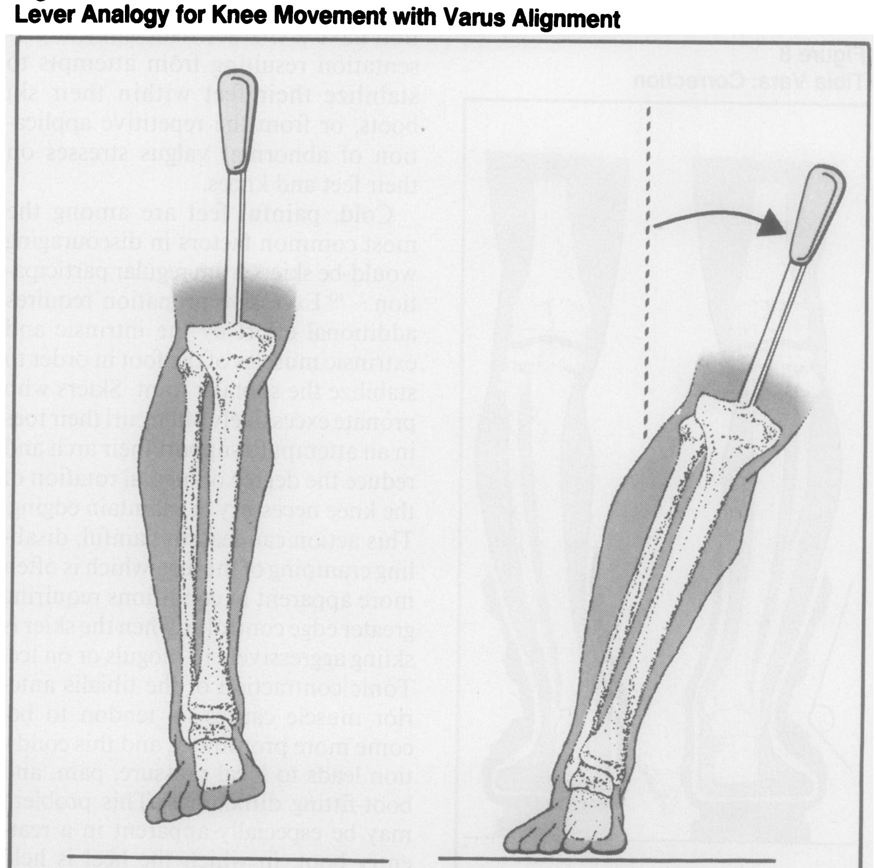
While it is important to make corrections based on the measured amount of varus alignment of the tibia, subtalar joint and forefoot, it is also essential to assess the adequacy of correction by repeating the functional test as described above. The skier assumes the functional skiing position while stand-

Figure 10
Varus Alignment and Pronation of the Foot



In the weight-bearing position the varus-aligned foot assumes a pronated position that is accompanied by obligatory internal tibial torsion with medial rotation at the hip and knee. Note that the midpoint of the patella is now in a more medial position relative to the second toe.

Figure 11A, 11B
Lever Analogy for Knee Movement with Varus Alignment

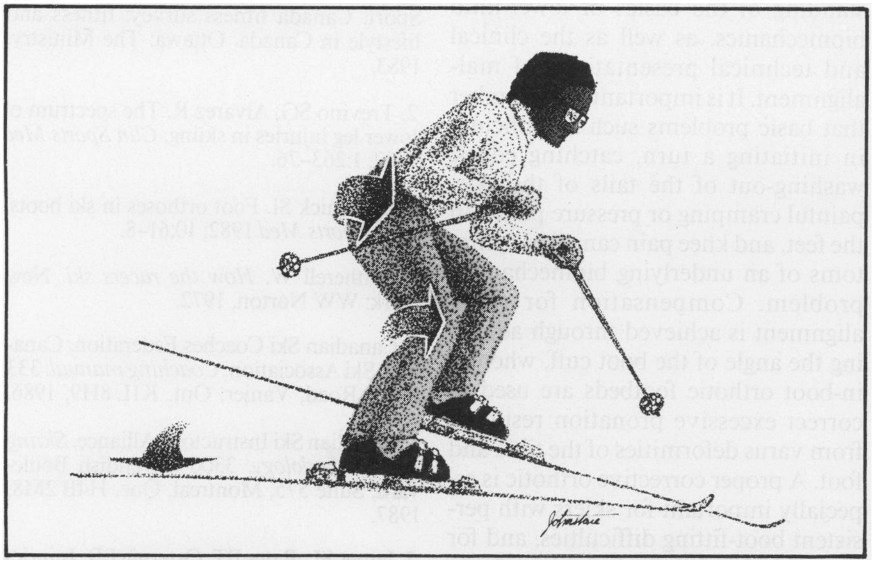


If the lower limb is thought of as a lever arm attached to the varus-aligned foot in the unweighted position, the greater the degree of varus, the further the knee must be directed medially before the medial aspect of the foot can be pressured.

ing on the corrected footbed on the floor, and a vertical line drawn from the midpoint of the patella should pass through the vicinity of the junction of the first and second toes. The adequacy of correction can be assessed by placing thin wedges (prescription pads work well) under the medial forefoot of the orthotic. If correction is inadequate, the skier will feel more stable with this addition. Conversely, if the orthotic is over-corrected, the vertical line will often fall more laterally, and the skier will feel uncomfortable while in the functional position and will complain that his knees are rolled outwards.

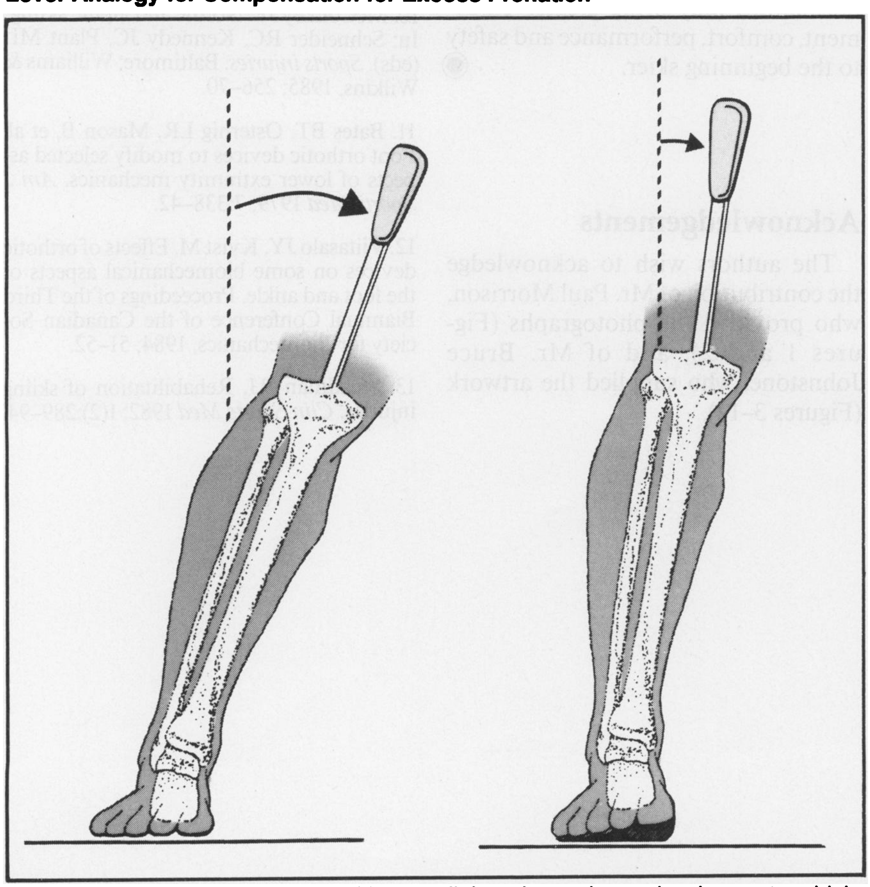
The type of orthotic device selected will depend on skier preference, skiing style, and cost. The device should be full length, molded to fit the contour of the foot, and have a perfectly flat sole to contact the boot board; it should also fit the liner of the boot without curling up around the edges of the toes. It is important to ensure that the boot board which underlies the liner also

Figure 12
The Consequences of Excess Pronation



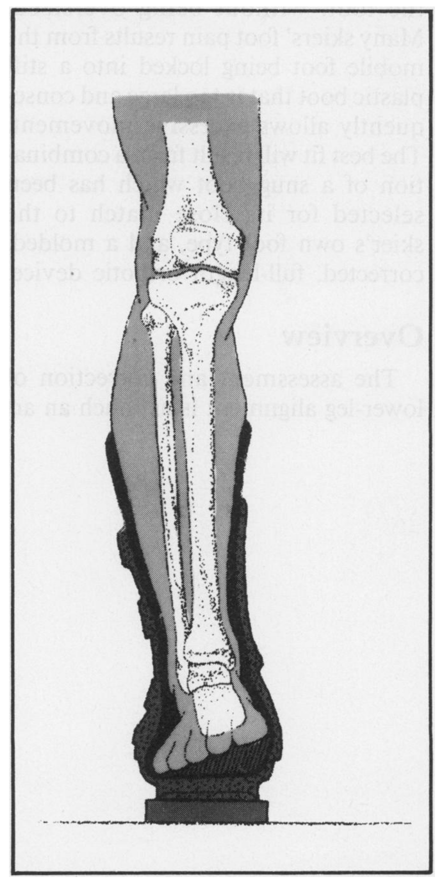
Despite medial rotation of the knee and hip, the skier is unable to edge the ski adequately, causing the upper body to rotate into the hill and preventing counter-rotation. This causes the washing out of the tails of the skis, skidded and banked turns, and an increased probability of falling into the hill. Élite skiers can overcome this tendency with exaggerated knee drive and increased counter-rotation, enabling them to edge the ski and keep their weight over the downhill ski.

Figure 13A, 13B
Lever Analogy for Compensation for Excess Pronation



The use of a corrective orthotic with a medial wedge reduces the degree to which the knee must be directed medially in order to pressure effectively the medial aspect of the foot.

Figure 14
Corrective Orthotic in the Ski Boot



The orthotic compensates for the varus alignment and supports the medial aspect of the foot. Note that the midpoint of the patella is now centred over the second toe.

has a flat surface. Some boards are contoured slightly to provide support under the arch, and this formation can cause excess local pressure or overcorrection with its resultant problems. Soft or padded orthotics are adequate, since compressive impact forces are generally low in skiing, the ski boot already provides a rigid encasing structure for the foot, and warmth and comfort are important. Neutral orthotics, or footbeds, available in many ski shops, provide good arch support and are often adequate for the recreational skier with a minor degree of varus alignment. These footbeds, however, lack built-in correction for rearfoot and forefoot varus, although it is possible to add appropriate posting to some types.

The type of ski boot selected will depend on many factors, including skiing style and ability, foot shape, and the price of the boot. Different manufacturers build their boots to fit different foot shapes, and it is important for the skier to choose a boot that is appropriate to his or her foot type rather than to insist on a particular brand name. The ideal boot allows adequate room for the foot, without being oversized. Many skiers' foot pain results from the mobile foot being locked into a stiff plastic boot that is too large and consequently allows excessive movement. The best fit will result from a combination of a snug boot which has been selected for its close match to the skier's own foot type, and a molded, corrected, full-length orthotic device.

Overview

The assessment and correction of lower-leg alignment is as much an art as it is a science. The skier's problems must be approached with an understanding of the basics of lower-limb biomechanics, as well as the clinical and technical presentations of malalignment. It is important to remember that basic problems such as difficulty in initiating a turn, catching edges, washing-out of the tails of the skis, painful cramping or pressure points in the feet, and knee pain can all be symptoms of an underlying biomechanical problem. Compensation for tibial alignment is achieved through adjusting the angle of the boot cuff, whereas in-boot orthotic footbeds are used to correct excessive pronation resulting from varus deformities of the tibia and foot. A proper corrective orthotic is especially important for skiers with persistent boot-fitting difficulties, and for racers and other competitive skiers whose technique suffers as a result of uncorrected alignment problems. Although correction of these abnormalities may represent a fine-tuning aspect for top-level skiers and does not replace proper attention to training and technique, correction of significant abnormalities may bring greater enjoyment, comfort, performance and safety to the beginning skier.

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