27 Cross-Country Skiing

Paul R. Langer

Cross-country (XC) skiing has evolved from a centuries-old means of transportation for populations living north of the Arctic circle to a sport and fitness activity enjoyed by millions of people worldwide [1]. Development of new ski techniques, better training and teaching methods, groomed trails, and technological advancements in equipment have made this activity more accessible and popular in recent years. The number of XC skiing participants in the USA fluctuates annually in part due to snow conditions. According to the Snow Sports Participation Survey published by Snow Sports Industry America 4.1 million participants skied at least 1 day in the 2014/2015 ski season. Seventy-five percent of those skiers are skiing on groomed trails [2].

XC skiing is a metabolically more efficient movement than running and walking because of the ability to glide on the ski as well as to use the arms and poles for propulsion. Gliding reduces the metabolic cost of skiing [3, 4]. One study showed that in terms of energy cost per distance travelled, XC skiing allows participants to move at double the speed of brisk walking for the same metabolic power [1].

There are two distinct techniques or disciplines utilized in XC skiing—classic and skate. There are also other variations of XC skiing that include backcountry and telemark skiing and a sport that combines the two called ski mountaineering but the focus of this chapter is on conventional XC skiing. The ski equipment utilized will vary depending on the technique, terrain, and performance level of the skier.

The classic technique has been used for centuries and likely evolved naturally because of its similarity to walking and running [5]. Skate skiing is a much newer technique which was introduced in the 1980s. It is a more efficient and faster means of moving over the snow—at least when on a groomed track [6]. Each of these techniques has variations on the standard form which are utilized depending on

P.R. Langer, D.P.M., A.B.P.M., F.A.A.P.S.M. (✉)
Private Practice Twin Cities Orthopedics, Adjunct Clinical Faculty,
University of Minnesota Medical School, Minneapolis, MN, USA
e-mail: paullanger@tcomn.com

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the terrain, snow conditions, skier ability, and speed. While running and walking are bipedal gaits, the use of poles makes XC skiing a quadrupedal gait. The key differences in equipment are that classic skis are longer but the poles are shorter than for skate skiing. There are differences in the waxing methods as well.

Classic Skiing

The classic discipline utilizes what is known as a “kick-and-glide” or “diagonal stride” technique and is the most similar to walking and running [7]. See Fig. 27.1. Research indicates that the amount of propulsion provided by the poles is variable but increases with slope inclination for both classic and skate [8].

Although there is not yet a universally accepted definition of the subphases of the classic ski gait cycle according to Barberis [9], there does seem to be agreement that there are, like running and walking, two primary phases of locomotion—glide phase and kick or propulsive phase. Smith subdivided the kick phase into an “early” and “final” kick [10]. In the terminal phase of classic glide, propulsion occurs as the skier pushes with the pole while kicking off the momentarily stationary ski and then transferring weight onto the gliding contralateral ski. There is a moment of gliding as the final component of the stance phase occurs on one limb (the propulsive limb) and as the contralateral limb (the glide limb) has finished the swing phase and begins to load on the opposite side. The glide phase that follows kick occurs as the posterior arm and pole are brought forward to plant the pole in front of the skier’s center of mass as the arm extends and opposite leg flexes at the knee and hip in early

Fig. 27.1 The classic XC ski discipline utilizes a kick-and-glide technique (photo credit Bruce Adelsman)

swing and then extends in terminal swing to slide the unweighted ski forward just before gliding on that limb.

Unlike skate technique which propels off of a moving ski, classic propulsion begins on a temporarily stationary ski [10]. The load on the stance limb and ski at midstance (just prior to kick) is highest at this point in the cycle and approaches 1× bodyweight [11]. This higher force allows the ski to flex and the "kick zone" or wax pocket of the ski then contacts and grips the snow in order to provide propulsion. The kick zone is an area of the ski bottom extending from the heel of the boot anteriorly 70–75 cm which is covered with a klister or grip wax which prevents the ski from sliding during propulsion [12]. The remainder of the ski—the tip and tail—are covered with a glide wax. The camber of the ski when not fully weighted allows the kick zone to lose contact with the snow while the tip and tail remain in contact to maximize forward glide.

Waxless skis use a raised fish scale type of pattern on the bottom of the ski's kick zone which provides grip on the kick, when the ski is pushed backward and glide when the ski is moving forward. Waxless skis are preferred by recreational skiers who would rather not to have to change wax regularly to adjust for different snow conditions and temperatures. Ski racers prefer wax for its performance benefits.

Double poling is used both in classic and skate skiing on flat terrain. It consists of the skier utilizing both poles simultaneously for propulsion while the skis remain evenly weighted and parallel. Propulsion comes exclusively from the upper body in this technique.

Fig. 27.2 The freestyle or skate skiing discipline (photo credit Bruce Adelsman)

Skate Skiing

Skate skiing is also sometimes called freestyle skiing (Fig. 27.2). The skate technique is very similar to ice skating in that the power-generating phase occurs off a foot and limb that is externally rotated in relation to the plane of progression. The popularity of skate skiing is largely due to the fact that it is metabolically more efficient and skiers can attain greater speeds [6]. Skate skiing must be done on a wide, packed, groomed skate deck. Poling is done with both poles simultaneously in synchronization with propulsion from each leg as opposed to the contralateral arm/ski motion in the classic discipline. Unlike classic skiing where the skiers' center of mass (CoM) changes minimally from medial to lateral, skate skiers shift their CoM significantly as they alternate propulsion from limb to limb.

There are variations of the pole and ski timing that skate skiers will use depending on the terrain. For example, some techniques are best for conserving energy and skiing flat terrain. Other techniques expend more energy but are better for sprinting and climbing. A skate skier provides ski propulsion by first gliding on the flat ski and then pushing posterior lateral while transferring weight to the medial foot and edging the medial ski edge into the snow in the terminal propulsive phase. The skate skier pushes off the ski as it is gliding anterior and lateral. The poles provide more propulsion in skate skiing than in classic which is why the poles are longer [13].

Pursuit or Combi Skiing

Some ski racing formats combine the two disciplines of Nordic skiing in pursuit racing. In this format, racers ski a set distance in one discipline and then the second half of the race is skied in the other discipline after changing skis and poles (and boots for those who choose not to use "combi" or "pursuit" boots). The skier who was first in the first discipline starts first and the other skiers are sent out after him or her based on the amount of time they were behind after the first discipline. The field then pursues and attempts to overtake the leader. This racing format requires that skiers be proficient at both the classic and skate disciplines.

XC Skiing Injuries

Overall, XC skiing has a relatively low incidence of both overuse and acute injuries. Estimates of overall injury rates vary from 0.1 to 0.5 injuries per 1000 skier days [6, 14, 15]. The lower extremity is the most common site of both acute and overuse injuries. Interestingly, one study found that XC skiers were injured more often while doing non-ski training activities [16]. Overuse injury risk factors are similar to other sports: training errors, poor technique, and improper equipment.

Acute injuries are typically caused by falls or collisions with stationary objects and are much more common on downhills than flat or uphill sections due to increased velocity [14]. Boyle and colleagues described the most common mechanism of acute injury to the lower extremity as “an external rotation abduction moment applied to an entrapped ski.” This mechanism of injury is much more common in Alpine skiing as the free heel of XC skiing bindings allows more freedom of movement of the lower extremity during a fall.

Chronic exertional compartment syndrome has a high incidence especially affecting the anterior compartment in elite skate skiers [17, 18]. High tibialis anterior muscle (TA) activation during both swing and stance phases of the ski cycle may be a mechanism of anterior compartment syndrome. It was initially speculated that the mass of the ski and boot required increased activation of the TA muscle during the swing phase and this was the most likely mechanism of injury but Federolf and Bakker’s EMG study in elite skiers with anterior compartment syndrome showed that differences in TA muscle recruitment patterns were more significant during the glide phase than during the swing phase indicating that the TA was also important in balance [19]. These high-activation patterns during both the glide and swing phases of ski gait likely contribute to the high incidence of anterior exertional compartment syndrome.

Low back pain is not uncommon in both classic and skate skiing due to repetition of hip and back extension. Iliotibial band syndrome, hamstring injuries, and chondromalacia patella are more common in skate than classic as reported by Schelkun [20].

In an injury survey study done at the American Birkebeiner ski race (the largest ski marathon in North America) in 1996, foot and ankle injuries were the most common injury followed by hand/wrist injuries [15]. First metatarsal phalangeal (mtpj) joint pain has been described as more common in classic skiing than skate [20]. Classic technique requires more dorsiflexion of the first MTP joint than skate skiing due to the demand for dorsiflexion required during the terminal kick phase of the ski cycle. Individuals with first MTP joint dysfunction such as bunion deformities and or hallux rigidus or other arthritic conditions of the great toe joint may be predisposed to pain in this joint in the classic XC discipline. Skating technique, which utilizes more lateral forces from the ski and more power from the poles for propulsion, does not require as much dorsiflexion of the first MTP joint.

XC Skiing Footwear

Vogel described XC ski footwear as a combination of an Alpine ski boot and a running shoe [21]. Ski boots will have different structural features depending on whether they are intended for classic or skate disciplines. There are also hybrid boots or “combi” boots which combine structural features that are suitable for both classic and skate disciplines. Combi boots are also sometimes referred to as “pursuit” boots because pursuit racers must ski both classic and skate disciplines. Hybrid boots offer cost savings and convenience over having to buy two different boots. Other variations in boot structure are influenced by the ability of the skier and snow surface. In general, recreational skiers tend to place a higher priority on warmth and comfort while racers may be willing to sacrifice some warmth and comfort for performance features in a ski boot.

XC Ski Bindings

Boots for XC skiing provide the means for transferring power from the foot to the ski through a secure binding system. So before we discuss the boots in detail we must first discuss bindings.

Bindings have evolved from leather straps and cable devices to three-pin and to today's most commonly used bar system. While leather and cable systems have become mostly obsolete, three-pin binding systems are still utilized for Nordic backcountry skiing but both modern classic and skate use bar systems. In the bar system, a steel bar is embedded in the distal end of the boot sole and is secured into a clip on the binding. This allows for a stable attachment of the boot but also freedom of motion much like a door hinge [22]. The free heel of Nordic ski bindings allows for more power during the propulsive phase in both classic and skate disciplines as the foot can plantarflex in order to maximize power transfer to the ski. The free heel also reduces (but does not eliminate) the risk of lower extremity fracture and catastrophic knee injuries. XC bindings do not release in a fall as they do in Alpine skiing. Ski-binding manufacturers may at some point introduce bindings that release in a fall but currently there *are no such bindings on the market.*

Unlike Alpine ski equipment manufacturers, who have standardized their systems so that all boots and bindings are compatible, there are two distinct bar-binding systems for XC skiing (Fig. 27.3). New Nordic Norm (or NNN) and Salomon Nordic System (or SNS) are very similar in appearance with a grooved plastic binding plate attached to a metal clip [23]. The grooved plate articulates with matched grooves on the bottom of the boot and allows for better control of the ski especially

Fig. 27.3 NNN ski bindings and boot

at high speeds and downhills when the boot is flat on the ski. The metal clip secures the bar at the toe of the ski boot. The main difference between NNN and SNS is the geometry of the longitudinal groove(s) on the binding plate and boot bottom. NNN uses two thin parallel grooves and SNS uses one wider groove. The newest version of NNN is NIS (Nordic Integrated System) where the ski manufacturers make the ski with an attached binding plate. This system is compatible with NNN boots and allows for the proper binding placement in the ski shop by clicking the binding in place without having to drill holes. SNS also has a newer binding system that utilizes two forefoot bars for attachment which is claimed to provide better control of the ski. One bar is at the distal aspect of the boot and second is just distal to the metatarsal-phalangeal joints. There are other variations of these two binding systems and technological and design advancements will likely contribute to further changes in the future.

In determining which binding system to utilize, most ski retailers advocate first fitting the boots and, once the most comfortable and suitable pair has been selected, then matching the binding system to the boot. The rationale for this approach is that boot comfort is so important and the differences between NNN and SNS binding systems are negligible for most skiers [24].

Nordic Ski Boot Structural Features

As with any athletic footwear, the functional requirements of XC ski boots dictate their design. Nordic boots need to provide weather protection from both cold and snow, moisture management as the skier perspires, efficient energy transfer from the foot to the ski, and comfort by combining fit, cushioning, and support characteristics. These functional requirements are achieved through structural design elements and the use of different materials.

In contrast to running footwear, there is very little published biomechanical research on the topic of XC ski footwear. Much of the available information is descriptive and utilizes manufacturer's proprietary marketing terms and does not include scientific validation. In addition to boots specific to backcountry, classic, and skate there are subcategories of ski boots within each discipline. Racing, sport, recreational, offtrack, and even boots specific to roller skiing (utilized as a training method on paved surfaces in warm weather) are offered by most manufacturers. Almost all boots are made from synthetic materials and consist of a stiff sole, an outer moisture/snow-resistant shroud, and an inner wrap for a snug fit. Most ski boots now have removable insoles which make it much easier to modify or customize the boot with foot orthoses (Figs. 27.4 and 27.5).

Uppers

The upper of the Nordic ski boot has a number of jobs to do related to performance and comfort. It must fit snugly enough to minimize foot motion within the boot.

Fig. 27.4 Classic ski boot

Fig. 27.5 Skate ski boot

Excessive foot movement within the boot wastes energy and causes skin irritation. The upper must also provide weather protection especially from wind, cold, and snow. Most uppers utilize multiple materials to provide weather protection yet breathability for internal temperature and moisture management. The closure systems may use zippers, laces, hook-and-loop, cable, or ratchet buckle systems or a combination of the above to secure the boot around the foot. The uppers of more expensive boots often have heat-moldable liners and/or shells which can be customized for comfort by a skilled boot fit technician. Skate boots and racing boots incorporate stiff heel counters and ankle cuffs to provide rearfoot and ankle support. Some manufacturers offer models with canting or cuff adjustments that allow for modification to address tibial varum and tibial valgum.

The height and stiffness of the boot cuff tend to be lower for classic and higher for skating and combi. Backcountry boots may build in a gaiter or snow cuff. The most common anatomical sites for foot discomfort related to the upper in a Nordic

Fig. 27.6 Outsole of NNN ski boot bottom and SNS profile boot top (note the two bars). The outsole of the top boot is made of carbon fiber

boot are the malleoli, heel, and metatarsal-phalangeal joints 1 and 5. The upper of the boot may be low cut or have a high cuff. Skiing on groomed surfaces makes it less likely that snow may get in the boot and the more uniform density of the snow surface makes high cuffs less necessary [25]. This will be discussed in more detail in the following sections.

Outsole

The function of the outsole is to provide a secure binding fixation point and efficient energy transfer from the foot to the ski (Fig. 27.6). The outsole is made of nylon, plastic composites, or carbon fiber. The torsional and longitudinal flex is less stiff for classic and more stiff for skating. Racing and high-performance boots will be more stiff both torsionally and longitudinally than touring and recreational boots for both disciplines. Recreational boots, with their more flexible soles, can lose 5% of energy during propulsion while the stiffest racing boots lose only about 1% [21]. Because stiffer boots tend to be less comfortable, even elite ski racers may choose a more flexible boot over stiffer race boot based on their comfort preferences or previous history of foot pain or injury.

Insole

The sock liner or insole of most boots is minimally cushioned or supportive. Fortunately, it may be removed easily to allow for modification or replacement with an aftermarket insole or custom foot orthoses.

Ski Boot Last

The fit of any footwear is determined by the last or the form around which it is made. The last will dictate the fit characteristics of the boot and includes toe box shape, heel height, width, and volume. The last of recreational XC boots tends to focus more on comfort and so tends to have more volume than racing boots. Racing boots, on the other hand, prioritize performance over comfort and tend to be manufactured on “performance lasts” which have lower volume interiors. The low volume allows the manufacturer to reduce weight and provides more efficient energy transfer from the foot to the ski.

In general, racing and high-performance boots are stiffer and lighter than recreational boots. Race boots may utilize carbon fiber in place of thermoplastics for the sole, heel cup, and ankle cuff because it offers increased stiffness at a reduced weight. A study on bicycling shoes found that stiffer shoes minimize energy loss during propulsion but they are more likely to cause discomfort [26]. High-end boot options also include thermoformable heel cups and ankle cuffs which can be individually customized. Finding the “perfect” boot for any skier, whether they are an elite racer or a beginner, is a matter of balancing their unique needs and preferences for performance and comfort.

Classic Ski Boots

As mentioned previously, classic technique is primarily a movement in the sagittal plane. For that reason the boot is designed to flex at the MTP joints and does not provide ankle support or rigid external ankle stabilizers as skate boots do.

Skate Ski Boots

Both the outsole and the upper of skate boots are stiffer than classic as skating requires less metatarsal-phalangeal joint flexibility and more ankle joint complex stiffness in the frontal and transverse planes. Torsional stiffness of the outsole minimizes lost energy and allows for better edge control of the skis [27]. The external ankle cuff provides medial and lateral stiffness yet is hinged to allow for ankle dorsi- and plantarflexion. Hladnik stated that the torsional stiffness of the sole and transverse stiffness of the ankle of the boot should be as “high as possible” in order to provide optimal transfer of power [28].

Combi Boots

For skiers who prefer to have one boot for both disciplines, combi or pursuit boots are suitable. They combine some of the features required for each discipline. The outsole stiffness cannot be adjusted but the ankle cuff may be adjustable or removable to allow quick and easy transition.

Boot Fit and Comfort

XC ski boots should fit "comfortably snug." Skiers should be fit while wearing the socks they plan to ski in. Recreational skiers often choose thicker, warmer socks than racers who may prefer thinner socks. Ski boots must be fit well in terms of the foot shape and length in order to maximize comfort and minimize pain. A boot that is too tight will cause pressure on the toes and restrict blood flow to the feet. A boot that is too loose will cause blisters, waste energy, and compromise control of the ski due to movement of the foot within the boot. Most boot fitters agree that the toes should be lightly touching the front of the boot when standing. Classic skiers should flex the boot as they would while in the kick phase of the ski cycle to ensure proper fit and skate skiers should feel light toe pressure while standing on a single leg.

Fortunately, when advising patients on selecting athletic footwear regardless of the sport, the best evidence points to focusing on comfort [29]. Miller and colleagues found that footwear comfort seems to be related to fatigue, injury development, and performance. Fit, based on foot shape, is the most important factor in comfort followed by skeletal alignment. The stiffness and cushioning of the footwear were important but still required good fit to be perceived as comfortable by test subjects [30, 31].

Comfort features of a ski boot such as cushioning and flexible soles may feel good but are less efficient in transferring energy from the foot to the ski. Conversely, performance features such as a minimal cushioning and stiffer flex allow for more efficient energy transfer but provide less comfort. Comfort is subjective and cannot be measured [32]. Athletes prioritize comfort and performance features differently, so it is best when fitting boots to allow the skier to make comparisons and then select based on their personal preferences.

Aftermarket Ski Insoles

The vast majority of research on foot orthoses is done on walking and running gait and not on skiers. Off-the-shelf insoles are marketed to XC skiers as products that can improve comfort, decrease the risk of injury, and/or improve performance. Many retailers offer both customizable insoles and standard insoles. Standard insoles can vary significantly in terms of cushioning and stiffness. The customizable insoles are usually heat-molded to the arch by a technician in a weight-bearing or semi-weight-bearing position. It is common that the insole manufacturers educate and train retail ski staff according to their own philosophies often using self-serving and biased information that lacks scientific validation.

Considerations for Insoles and Custom Foot Orthotics

It is well established that humans do not respond in systematic ways to biomechanical interventions, so clinicians must rely on the best evidence, their clinical experience, and training to determine the optimal interventions for any given patient. This section does not discuss pathology-specific orthotic prescriptions but rather focuses on general insole and orthotic concepts in regard to XC skiing.

As with any footwear intervention, the biomechanics of the activity and the structural features of the footwear need to be considered when prescribing and manufacturing devices for the unique needs of the athlete. Medical professionals always have to be aware that the foot orthoses do not function in isolation—it is one component of the foot-shoe-ski interface. For high-level skiers it may be necessary to send the ski boot to the lab along with the cast in order to optimize the fit for custom foot orthoses. Because a flat ski glides more efficiently than a ski on edge, the goal of the orthoses should be to balance the skiers foot alignment in the frontal plane to maximize the time spent in a flat ski position. A hyperpronated (or planus) foot would be more likely to overload the medial edge of the ski as the rearfoot everts and the medial longitudinal arch collapses. Conversely, a supinated (or cavus) foot would tend to overload the lateral edge of the ski due to rearfoot inversion and medial longitudinal arch rigidity and/or a plantarflexed first ray. Forefoot-to-rearfoot malalignments must be balanced with the foot orthotic device in both conditions as well.

For both XC disciplines, efficient ski technique is dependent on optimal single-leg balance as the skier has to be able to maximize glide on each ski to conserve energy. Research has shown that postural sway increases with lower extremity muscle fatigue [33]. It has been speculated that molded insoles have the potential to delay the onset of fatigue and to improve proprioception which could then improve balance. A systematic review by Christovao and colleagues in 2013 found that insoles of various designs improved postural balance and control [34].

Poor skiing technique and/or poor balance have been implicated as issues that may contribute to excessive frontal plane motion resulting in less than optimal performance and potentially increasing the risk of falling and overuse injury. Mattacola and colleagues found that single-leg postural stability was improved in subjects with rearfoot malalignment (varus or valgus > 5°) when using custom foot orthoses [35]. In fatigued, uninjured subjects other researchers found that semirigid custom orthoses significantly reduced postural sway [36]. Although these studies were not done on XC skiers, balance is such an important part of good ski technique that they provide a potential reference point for use of orthoses to improve a component of balance and secondarily improve performance and decrease risk of injury in XC skiers.

In regard to injury, a study on the Swiss national ski team concluded that biomechanical interventions which included custom foot orthotics reduced pain and overuse injuries over a 3-year period [37].

Summary

The two disciplines of XC skiing use slightly different equipment and footwear which are unique to the respective technique demands of each. Ski boots must combine comfort and performance features based on the personal preference of the skier. There is adequate evidence in the research that insoles and orthotics can improve balance and delay fatigue which may result in improved performance and/or reduced injury risk. Further research is needed however.

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