

Clinical Commentary/Current Concept Review

Enhancing Return to Alpine Skiing: Integrating Perceptual-Motor-Cognitive Considerations in Testing and Progressions: A Clinical Commentary

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Keywords: ACL, Alpine Skiing, Return to Sport, perceptual-motor-cognitive rehab

<https://doi.org/10.26603/001c.120285>

International Journal of Sports Physical Therapy

Vol. 19, Issue 7, 2024

Alpine skiing poses significant risks for anterior cruciate ligament (ACL) injury at both recreational and professional levels, which is compounded by high rates of re-injury. Despite the existence of return to sport (RTS) and return to snow protocols, the frequency of ACL re-injury has not been mitigated, raising doubts about protocol effectiveness. Current RTS protocols primarily focus on biomechanical and neuromuscular factors in isolation, neglecting the important perceptual-motor-cognitive changes associated with ACL injuries and the high cognitive demands of skiing. The purpose of this clinical commentary is to address the perceptual-motor-cognitive demands specific to alpine skiing, evaluate RTS testing for skiers, and propose updated standards for testing and return to snow progressions that incorporate these considerations.

Level of Evidence

5

INTRODUCTION

Participation in alpine skiing, whether recreationally or professionally, has a high risk of injury. The injury rate for recreational skiers was approximately 0.5-1.98 per 1000 skier days, or approximately one injury per 10,000 lifts rides.¹⁻⁵ Knee injury accounts for 27-41% of all injuries at ski resorts, with an anterior cruciate ligament (ACL) and medial cruciate ligament (MCL) sprain being the most common diagnoses.⁶⁻¹¹ In professional skiing athletes the injury rate is even higher, at 36.2-36.7 injuries per 100 athletes, with the most common injured body part also being the knee at 35.6%, consistent with recreational skiing statistics.¹² One-third of injuries were considered severe, resulting in a loss of training and competition for a minimum of 28 days or more.^{1,12}

Specifically among skiers, 19-46.7% of competitive alpine skiers suffer a re-injury to their reconstructed ACL or contralateral ACL, which is consistent or more frequent than the general athletic population.¹³⁻¹⁶ Multiple studies describe functional asymmetries and deficits that persist

after return to play (RTP) in ACL reconstructed athletes that could possibly explain this high injury risk.^{13,17-20} Despite return to sport (RTS) and return to snow protocols attempting to provide quantitative testing to ensure sport readiness and reduce reinjury risk, the rate of ACL re-injury remains high. RTS protocols are primarily based on biomechanical and neuromuscular function including range of motion, strength, and functional tests such as jumping and hopping and sport specific testing.²¹ Return to snow protocols for high level skiers include similar multifactorial measures, but also suggest supervised progression of “on-snow” drills to return to full function and racing performance.^{22,23}

An aspect of ACL injury and recovery that has unique implications for the high-speed perceptual-motor-cognitive demands of skiing is the neuroplastic adaptations (altered brain and neural activity) recently described to be associated with the injury. Perceptual-motor-cognitive is an integrated demand that includes maintaining dynamic joint stability in a highly variable perceptual environment while engaged in very rapid cognitive updates with distrac-

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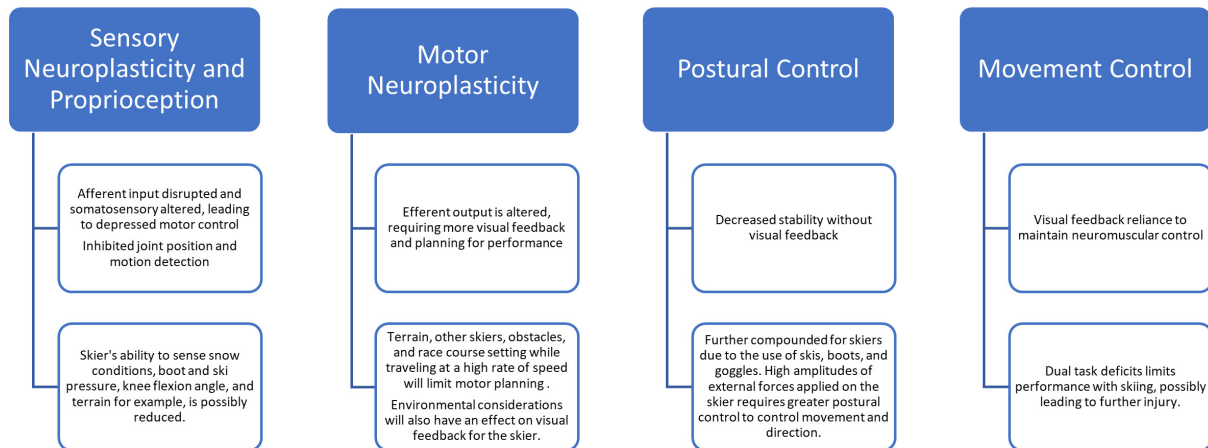


Figure 1. The conceptual framework for neurologic and visual-motor adaptations after ACL injury, and the perceptual-motor-cognitive neuroplastic adaptations that possibly occur within alpine skiing.

Adapted from Grooms et al 2015.²⁴

tors. Typically, rehabilitation and RTS testing after ACL reconstruction (ACLR) focuses on restoring functional ability (addressing interlimb asymmetry in muscle power, rate of force development, maximal strength) and psychological readiness.²¹⁻²³ However, injury deafferentation and associated pain, muscle atrophy, and movement compensations contribute to neuroplastic adaptations and variations in motor control upon return to sport.²⁴ Specifically, it appears that the injury associated neuroplastic alterations result in changes in perceptual-motor-cognitive neural activity that may explain the elevated dual-task cost and injury risk.

The loss of movement quality and dual-task cost for those with ACLR is theorized to be secondary to the injury disruption in sensory processing resulting in increased utilization of visual input and visual-cognitive processing capacity to compensate to maintain dynamic joint stability.²⁵⁻³⁷ However, skiing requires sensory processing in a rapidly changing external environment that can overwhelm the developed neural compensations and may contribute to a reduced ability to maintain coordination and increase contralateral ACL injury or re-injury risk.³⁸⁻⁴¹ Thus, to better prepare athletes and ensure adequate sport readiness with RTS testing clinicians may consider creating different challenges to sensory and cognitive processing that have implications for maintaining neuromuscular control in sport. Currently, there is a gap in knowledge regarding how best to quantify perceptual-motor-cognitive demands in sport, especially in alpine skiing, to inform the safe return to snow after an ACL injury. The purpose of this clinical commentary is to address the perceptual-motor-cognitive demands specific to alpine skiing, evaluate RTS testing for

skiers, and propose updated standards for testing and return to snow progressions that incorporate these considerations.

ALPINE SKIING AND PERCEPTUAL-MOTOR-COGNITIVE DEMAND

For alpine skiers specifically, there are a variety of environmental and equipment considerations that contribute to external perturbations and cognitive load. Environmentally, colder weather affects fine motor control, postural control, balance, and proprioception likely attributed to a decrease in muscle contraction velocity and nerve conduction velocity.⁴²⁻⁴⁴ Variable wind and snow conditions can reduce visibility and create unfavorable changes to the course surface; however, there is no agreement among coaches and researchers about which snow conditions, snow-covered or water-injected, are safest for alpine skiers.⁴⁵ Differing snow conditions within a course can bring athletes close to their physical and technical limits, possibly increasing risk for injury.⁴⁵ Changes in course conditions from those at which the athlete practiced and trained would influence their sensory predictions and may slow postural corrections, increasing risk of injury at high competition speeds. Course conditions and neuroplasticity of injury could limit overall performance if perceptual and cognitive processing speed is not at a level at which the skier is accustomed to.

EQUIPMENT CONSIDERATIONS ON PERCEPTUAL LOAD

Skis are also an equipment-related ACL injury risk factor due to differences in ski length, tip width of the ski, standing height at the rear ski binding component, and in standing height ratio (percentage between front and rear component heights and how it relates to the angle of the boot sole when inserted into the binding).⁴⁶ A ski bindings DIN (Deutsches Institut für Normung, German Institute for Standardization) setting or release force of the ski is equally important for preventing injury, failure of binding release at the moment of accident, the ski acts as a lever to bend or twist the leg, leading to a potential severe knee injury.⁴⁷ Failure of binding release during a fall resulting in an ACL rupture has been often reported in falls (78%) and is significantly more often with females compared to men.⁴⁸ Although ski and boot technology has improved in recent years in attempts to enhance skier safety, overall, the ski-binding interface, bindings, and boots impair proprioception from the lower extremity, thus increasing the risk for falls and mistakes, and cause an increased strain on the ACL at higher loads.⁴⁹⁻⁵¹ Helmets and ski goggles have also been shown to limit visual performance, which can reduce reaction time to peripheral stimuli or limit visual input for postural control, thus putting a skier at risk for injury.^{52,53}

ENVIRONMENTAL & CONTEXTUAL CONSIDERATIONS

The unique high speeds of alpine skiing places additional cognitive and motor planning stress that can be influenced by subtle alterations in course terrain. Course structures such as rolling and dipping terrain transitions, placement and number of gates during high level racing, jumps, and speed of the terrain/slope reduces the time that skiers have to anticipate and adapt to technically demanding sections, increasing the risk for mistakes.⁵⁴ For the recreational skier, while variable skiing environments are comparable with alpine ski racers, there is also the added perceptual-motor-cognitive load of other skiers sharing the same terrain. This could have a negative impact on skiing performance through impaired sensorimotor prediction due to added unanticipated reactions and rapid fluctuations in distracted attention from skiing, while maintaining neuromuscular control and efficient visual processing.

Athletes following ACLR have been theorized to have lost sensory integration efficiency, requiring increased neural activity to perform a motor task compared to a control group.⁵⁰ The amount of afferent information from external perturbation that a skier must process is accompanied by the intensive motor requirements of downhill skilling with increased muscle force and coordination timing demands. The need for high level technical skills and sensory processing has been shown to improve the ability to anticipate a collision or fall, reducing the impact severity for athletes.⁵⁵ The combination of ACLR associated neuroplastic alterations and skiing perceptual-cognitive demands may contribute to the high rates of re-injury in this population, despite RTS testing suggesting that functional recovery has occurred. This points to the need to consider aspects of sport requirements and injury adaptations not

typically captured in RTS testing. To that end the authors suggest that perceptual-motor-cognitive additions could be a missing element and suggest methods to accommodate it in the return to snow progression.

RTS TESTING AND SKIING

Despite accumulating evidence that ACL injury induces compensatory neuroplastic adaptations within neural circuits, current return-to-snow testing does not adequately capture the ability to effectively respond to all aspects of the intense perceptual-motor-cognitive demands that can be encountered when skiing. Current RTS decision-making is primarily based on maximal muscle strength testing and closed motor skills, reaching a specific milestone that nears limb symmetry or allometric scaling with normative data.^{21,56} Multiple studies report a battery of objective neuromuscular or psychological readiness testing that may include variable challenges to simulate sport related movements, however, comprehensive assessment of perceptual, motor, and cognitive capabilities is often lacking within RTS testing.^{21-23,57} In the clinical setting, it is difficult to simulate the complex sport environment of skiing due to the inability to simulate the forward inertia of skiers via the downhill landscape, requirement of equipment, and snow variations. However, it is possible to challenge the perceptual-motor-cognitive demands of skiers during testing by integrating perceptual-motor-cognitive elements into the established RTS tests within this population. As highlighted previously, this appears to be an element that could be missing from testing and return to snow progressions and is essential for alpine skiers. Common in athletics including alpine skiers, additional functional movement and strength tests performed in RTS testing focus on the single leg hop, single leg crossover hop, and the single leg jump/strength testing on force plates.^{21,22,58,59} Without visual-cognitive stress to simulate the sporting environment, athletes could possibly compensate and give the appearance of restored function, and if released to sport early, can possibly still be at high risk for re-injury. The authors suggest that a full skiing environmental simulation is not required, but more simply challenging of the underlying physiology required by the sport. Just as strength training improves capacity for muscular performance, so to can coordination training under perceptual-cognitive demands improves capacity to maintain dynamic joint stability upon returning to the snow environment. In this way the authors challenge the elements of rapid decision making and motor plan updating, attention on a changing environment and cognition directed away from knee kinematics as key constructs to train the underlying physiology to provide the capacity transfer to skiing.⁵⁸

INTEGRATING PERCEPTUAL-MOTOR-COGNITIVE ELEMENTS INTO RTS TESTING

While standard functional testing allows for ease of set up and replication, and valuable baseline data about limb

asymmetries post ACLR; standardized tests lack perceptual-motor-cognitive elements that could better simulate sport demand for the alpine skier. RTS testing with perceptual, motor, and cognitive features could be utilized to fully understand the dual task deficit that occurs after an ACL injury. Researchers are developing reliable and replicable tests with perceptual and cognitive stress modified from common functional RTS challenges.

UPGRADING THE HOP TESTS AND VARIATIONS IN PERCEPTUAL-MOTOR INTEGRATED TESTING

Hop tests are a common measure to determine if an athlete is fit to return to sport but are often performed without the dual task challenged needed to replicate the demands of skiing. Recent research has been focused on improving generic hop tests, by adding elements of perceptual-cognitive elements of reaction time, visual tracking, spatial awareness, and visual working memory along with motor performance.⁶⁰⁻⁶² A jump test that may have greater applications to the stability required for skiing could be the visual-cognitive side hop test.⁶³ Skiers must overcome the dynamic balance of forces from gravity and vertical/horizontal ground reaction forces as well as utilize motor control to make turns possible. The visual-cognitive side hop test could possibly simulate the lateral ground reaction force that is exerted on the skier during a turn while providing a dual task similar to an alpine event.⁶³ It is also hypothesized that side hop tests can reveal greater asymmetries in athletes with prior ACL injuries as well as elicit greater knee valgus, hip adduction, and medial rotation.⁶⁴ These angles are often stressed in the various phases of a ski turn suggesting that this test could be effective in assessing return to snow capabilities.⁶⁵ Further jump-landings can be incorporated via a double leg take off with single leg landing with an unanticipated visuomotor stimuli indicating which leg to land on (left or right).^{66,67}

Similar perceptual-cognitive additions can be integrated into already commonly done strength and jump assessments in order to assess dual-task cost on rate of force development, reaction time, and peak force production. Simple computer programming, interactive LED training lights or even verbal/visual commands from a practitioner can be utilized to complement strength testing. For instance, an isometric closed chain single leg press at 60 degrees (meet resistance) or an 80/20 jump test on force plates can be tested with stop/go lights or screen programming. Strength, reaction time or force development can be compared to the uninvolved limb to see if a 90% limb symmetry index can be maintained under dual task challenged conditions (as will occur in sport/skiing).

QUANTIFYING PERFORMANCE

To determine reaction time, testing can be analyzed with applications and slow-motion video technology, which also enables the practitioner to analyze movement patterns. Movement patterns can also be evaluated in real-time with the landing error scoring system (LESS) or balance error scoring system (BESS), providing a movement quality out-

come to determine dual-task cost. Chabaan and colleagues developed a creative instrument in order to create both motor and cognitive tasks during functional testing (drop jumps, single limb jump tests, cutting) that can be easily applied and measured based on low or high tech resources within clinic.⁶⁸ A calculation for dual task cost was also proposed during specific motor tasks in order to quantify the motor performance and movement quality with or without cognitive load, in order to compare healthy and surgical limb. This concept of a dual-task cost application can also be provided to snow specific settings.

USING EQUIPMENT TO IMPROVE SPORT SIMULATION DURING TESTING

Replicating an alpine environment in clinic is difficult to adequately stress the skier for safe return to sport. Utilization of helmets and goggles during return to snow testing can limit visual field and proprioception, and more accurately reproduce challenges specifically for athletes trying to return to alpine skiing. For example, helmets and goggles can be applied to hop testing, balance training, lateral agility, and closed chain strength training. Furthermore, performance before and after equipment application can be measured while assessing limb symmetry (strength, reaction time, and distance), and quality of motion. The added visual perturbations and perceptual-cognitive load with equipment changes could be an effective tool to bridge in-clinic return to RTS testing with return to snow training and possibly reduce sensorimotor prediction errors resulting in poor performance. Perceptual-cognitive challenges should continue to be applied for alpine skiers, both recreational and professional, when cleared to return to snow.

RETURN TO SNOW PROGRESSION INCLUDING PERCEPTUAL-MOTOR-COGNITIVE ELEMENTS

Progression-based return to snow is may ultimately prove to be highly beneficial for skiers returning from an ACL injury. Kokmeyer and associates suggest a return to snow program that is progression-based with differing intensities, focus, and durations as well as example drills that can be utilized while on snow.²³ They recommend that after a skier completes their clinical functional sports test, they start a return to snow program over the course of 8+ weeks, typically during their 6-9 months post operative timeline.²³ Although directed primarily at elite alpine skiers, a similar strategy can be utilized towards the recreational skier, under the supervision and guidance of a medical provider.

The return to snow program described by Kokmeyer and colleagues included a variety of drills that challenged proprioception but could be further modified to progress perceptual-motor-cognitive load while on snow.²³ Perceptual load was challenged by adding various challenges and drills on a single leg when turning or sliding. Additional challenge during single leg drills can be progressed by varying ski lengths and boot stiffness. Although an effective return to snow progression, there is nothing specific on visual perturbations, environmental considerations, and ways that

multiple challenges can be combined to adequately perceptually, cognitively, and motor stress these athletes. Adding perceptual-cognitive challenge to these drills can be achieved by reducing visual input, adding reaction time or anticipatory elements, and varying environmental constraints (Tables 1 and 2). Exercise progressions on snow can also be altered based on the level of skier in order to adequately test and assess their ability to perform an activity with cognitive stress (Tables 1 and 2). Recreational skier progressions may involve stressors more focused on visual and environmental elements whereas professional skiers could focus more on visual perturbations, varying proprioceptive and perceptual inputs (turns/equipment/course terrain), and reactionary elements similar to that in the racing environment. Perceptual-motor-cognitive stressors should not be progressed by adding multiple elements in a singular session, but to implement one element at a time and evaluate responses before progressing. For example, introducing night skiing (visual challenge) with a new proprioceptive challenge (such as a different ski length than what they usually ski with) may produce too much of a challenge for the athlete resulting in reduced performance. Although difficult to objectively ensure return to competition readiness, especially with alpine skiers and on-snow progressions, drills designed to stress perceptual-motor-cognitive elements would help simulate an environment and cognitive load that would possibly give a skier the psychological and cognitive capacity to return to prior level of function. As opposed to depending on physical recovery and hoping that performance is not degraded when under the cognitive demand of sport.

It is important to note that the return to snow progression doesn't look at a specific moment in time, but throughout the entire continuum of rehabilitation in order to return to snow. In order to safely and effectively return to snow at a high-performance level, whether that is recreationally or professionally, consistent quantitative and qualitative testing is required at multiple timelines during the rehabilitative program. Passing objective criteria in clinic allows the athlete to return to participation of on snow training activities. It is stressed that until guidelines are established for return to participation with dual-task testing, caution is urged for athletes that have large dual task costs with traditional testing battery under perceptual-cognitive-motor load.⁶⁸ The athlete must also safely perform all training progressions with added perceptual-cognitive-motor elements, if possible, under the supervision of coaching and medical professionals in order to return to snow. Quantification of readiness for a professional athlete would be prior level of performance (no more than a 10% degradation in dual task cost) during time trials in a simulated environment comparable to that of a professional event with appropriate motor control. Monitoring of all elements of the return to snow continuum allows practitioners to make informed decisions and increase the likelihood that the athlete returns to skiing at a high level of performance.⁶⁹

CONCLUSION

In conclusion, alpine skiing is a high-risk sport for both the recreational and high-level athlete, with a high rate of re-injury seen in athletes that have suffered an initial ACL injury and reconstruction. This can be attributed to several unique factors included in the sport of alpine skiing, including equipment, positions that place extreme forces and torques on the knee, and an extraordinary demand for neuromuscular control, endurance, strength, and eccentric control in the lower extremity.²⁵ Alpine skiing is an open-skilled sport, where skiers are exposed to multiple stimuli in which athletes must make decisions in an unpredictable, dynamically changing environment.³⁸ Alpine skiers who suffer from an ACL injury, despite reconstructive surgery, demonstrate perceptual, cognitive, and motor processes that possibly induce a neuroplastic change within the athlete thus increasing the risk of re-injury. These deficits are routinely trained within a clinical setting in order to return an athlete to their sport at a high level; however, a patient's ability to perform under dual task stress is typically not measured due to the difficulty of objectifying cognition and performance. Strategies have now been introduced to assist in the assessment of an alpine skier's return to snow functional testing in conjunction with neurocognitive and physical performance. Furthermore, perceptual-motor-cognitive challenges can be added to an already established return to snow program to improve safety in a skier's progression to prior function and bridge the gap between clinic and on-snow rehabilitation.

DISCLOSURES

Dustin Grooms reports the following grants and potential conflicts of interest:

US Department of Department of Defense Congressionally Directed Medical Research Program Peer Reviewed Orthopaedic Research Program (research award W81XWH-18-1-0707); National Institutes of Health/National Institute of Arthritis and Musculoskeletal and Skin Diseases (R01AR076153, R01AR077248) and Consulting Fees from Kinesport physical therapy (France).

ACKNOWLEDGEMENTS

The authors would like to express deepest appreciation to Howard Head Sports Medicine and the Howard Head Sports Residency Program for the support of this project. Special thanks to Dane Ringquist DPT and Delaney Smith for photography, as well as Brooke Milliet DPT for her assistance with skiing specific perceptual-motor-cognitive task development.

Submitted: October 04, 2023 CDT, Accepted: June 12, 2024

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Table 1. Return to snow with examples of perceptual-cognitive-motor progressions for the recreational skier

Perceptual-Motor-Cognitive Challenge		Visual	Proprioceptive	Reaction time/ anticipatory	Environmental Changes
Challenge Progression	Easy	Sunny/Night skiing Dark or light tint goggles	Wedge vs hockey stop	Distracted skiing (music, mental tasks, etc)	Groomed runs
	Moderate	With/without goggles Skiing with visual tracking/reading (reading trail signs for example)	Sliding vs Carving Varying Muscle Fatigue	Randomized stop/starts Speed variability	Wet/sticky snow Powder days
	Hard	Reduced visual field goggles	Ski length, width, type, skiing with/without pole Varying boot stiffness	Randomized turns	Foggy/low light Variable slopes
	Advanced	Eyes closed or Head turns	Inside edge skiing	Skiing in trees/ moguls	Moguls
	In-Clinic Options	LED training lights Visual cue cards Eyes closed Stroboscopic glasses	Double or single leg balance on ½ foam roller or BOSU ball	Unanticipated Perturbations from PT or exercise ball Virtual reality LED training lights Visual cue cards	Large gym with distractions Loud music Varying surfaces (turf, grass, track, concrete, etc)

Different aspects of perceptual-cognitive-motor challenge should not be progressed all at one time, for example, skiing at night on a mogul run. Challenges should be progressed one at a time in order to allow safe and achievable goals for the recreational skier.

Table 2. Return to snow with examples of perceptual-cognitive-motor progressions for the professional skier

Perceptual-Motor-Cognitive Challenge		Visual	Proprioceptive	Reaction time/ anticipatory	Environmental Changes
Challenge Progression	Easy	Skiing with gaze stabilization	Double leg slide slipping, diagonal, sliding turns.	Coach led randomized stops and starts	Groomed runs
	Moderate	Number of gates and distance between gates Skiing with head turns for vestibular training	Single leg sliding turns with heel lift or cross hip opposite ski (Javelin Turn) Varying boot stiffness and ski length/width	Coach led randomized turns Stubby/brush track	Cold vs Hot Temperatures Variable Slopes
	Hard	Reduced visual field goggles Stroboscopic glasses	Turns with 1000 ft stepping	Multiple practice courses on slope Variable slalom course	Snow coverage course Foggy/flat light
	Advanced	Eyes closed	Turns with one leg lifted	Vary racing events: downhill, super G, giant slalom, slalom	Injected Course
	In-Clinic Options	LED training lights Visual cue cards Eyes closed Stroboscopic glasses	Double or single leg balance on ½ foam roller or BOSU ball	Unanticipated Perturbations from PT or exercise ball Virtual reality LED training lights Visual cue cards	Large gym with distractions Loud music Varying surfaces (turf, grass, track, concrete, etc)

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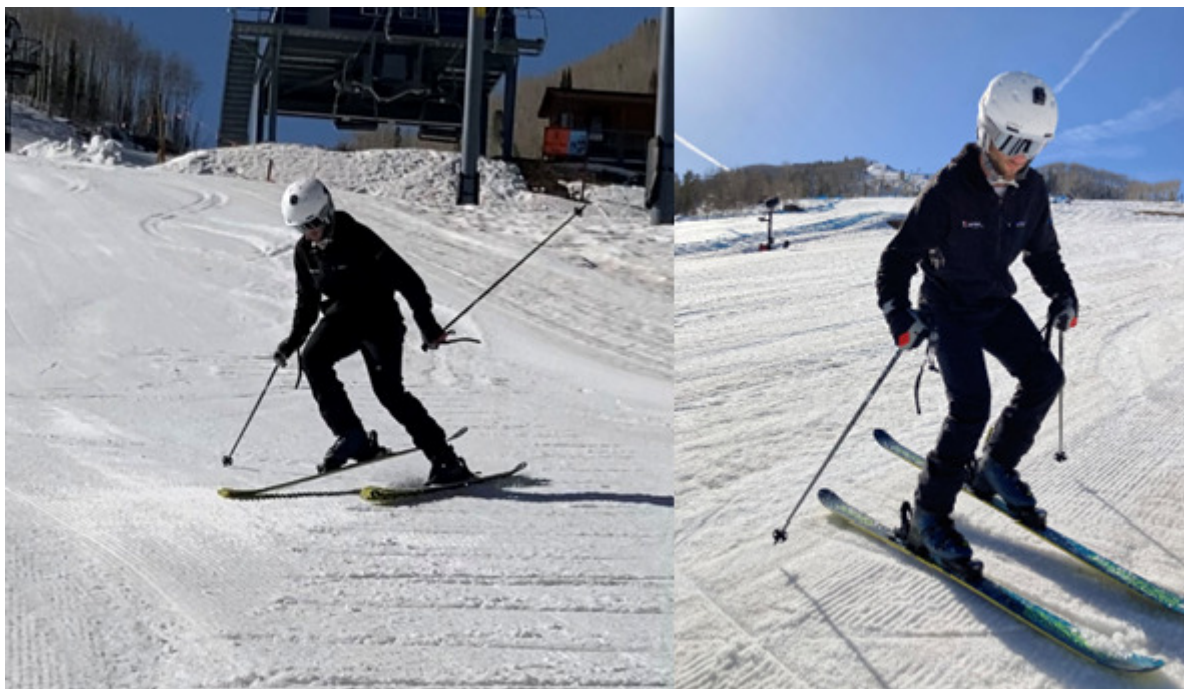


Figure 2. Turns with inside ski heel raised to increase perceptual stress on outside ski during turn.



Figure 3. Javelin turns or opposite ski crossed hip opposite ski turns to increase perceptual stress on outside ski during turn as well as postural stress under load.



Figure 4. Single leg turns (same leg turning both directions) for perceptual and postural stress on a single leg during different angles and torque of a turn.



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