Cross-Country Ski Exoskeletons: An Accessible and Safe Way to Enjoy Winter Sports

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Abstract

Cross-country skiing with exoskeletons could give broader population access to winter sports. We propose a preliminary approach based on a mechanical analysis starting from the kinematics and then incorporating the kinetics and constraints. We analyze how to safely bind the exoskeleton, skis, and user for safe use. The resulting requirements seem achievable.

Keywords— Cross-country skiing, powered exoskeleton, requirements, risk management

1 Problem Formulation

Cross-country skiing is an enjoyable activity, safer than alpine skiing due to lower energy impacts. Unlike its more risky counterpart, alpine skiing, Morrissey et al. [2] found that the injury rate for downhill skiing was approximately 2.5 times higher than for cross-country skiing. Despite its lower injury risk, cross-country skiing is still an endurance sport that requires exercise and provides related health benefits. By adapting to the level of the user, including those with disabilities, an exoskeleton could make this activity more accessible. We will analyze the movement in cross-country skiing in terms of kinematics and dynamics and discuss the related risks. We will then select an existing exoskeleton and evaluate the required adaptations and prospect technical solutions regarding the issues we will have previously identified.

2 Analysis of the movement

Cross-country skiing can be performed using either the classic technique or skate skiing. Classic skiing involves push-and-glide motion (see Fig 1 A, B), where the skier moves their skis parallel to each other in a straight line. Skate skiing mimics the motion of ice skating; the skier moves the skis in a V-pattern, pushing off to the side with one ski and then gliding on the opposite ski (see Fig 1 C). Classic skiing is generally easier to learn and requires less fitness and technique compared to skate skiing. Additionally, classic skis are typically wider and more stable than skate skis, providing better control for beginners. We chose, thereafter, to use the classic skiing technique.

Pushing and Gliding Phase: In classic cross-country skiing, the kick-and-glide motion is used to generate forward momentum and maintain bal-

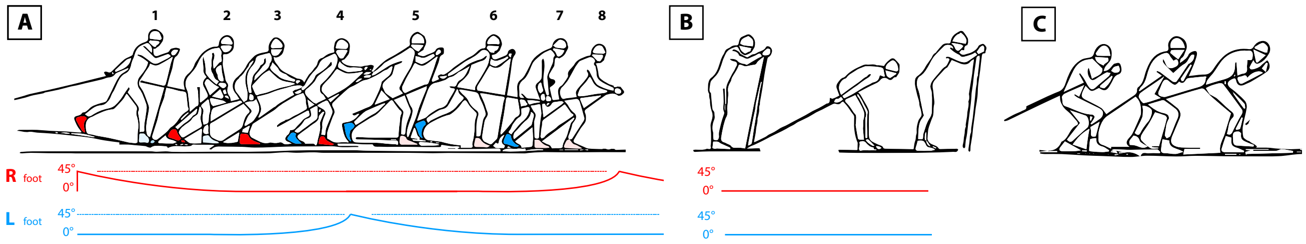

Figure 1: Movement cycles from the investigated techniques in the classical style cross-country skiing. A) The diagonal stride, B) double poling, C) skate skiing. Image taken from [1] and modified

ance. The skier starts by placing their weight on the grip zone of one ski and extending the leg to push off the snow. The opposite ski glides forward on the snow, allowing the skier's momentum to carry them forward. A study in [3] showed that each technique had different characteristics in terms of the propulsive and gliding phases, with the classic diagonal stride having the longest gliding phase and double poling having the shortest. Moreover, it also found that muscle activity varied between the techniques, with different muscle groups being activated during the diagonal stride and double poling. This means that the exoskeleton can be designed to automatically detect each skiing phase and adapt its support to the type of motion. In this context, the interconnection between the feet, the ski, and the exoskeleton is a crucial factor in ensuring optimal performance, safety, comfort, and stability for the user. We will address this in the next section.

Force Involved: The purpose of an exoskeleton is to reduce fatigue by providing additional support, thus decreasing the load on the skier's muscles and helping him to ski longer without exhaustion. In [4] eight professional skiers with a body mass of $71.6 \pm 6.8kg$ performed a study in which was found that the average horizontal and vertical pole forces were 6% and 7–8% body weight, respectively, and, in addition, they did not change much with higher skiing speed. Similarly, it was found that the sum of averaged vertical ski forces and pole forces over a step cycle remained the same between different skiing speed conditions (661.2 ± 62.9, 661.5 ± 65.1, 645.1 ± 87.8, and 649.7 ± 66.9 N for SLOW, MID, FAST, and MAX, respectively).

Risks involved: Cross-country skiing faces two significant risks: falls and collisions. Potential causes include slippery snow, ice, wet and cold conditions, uneven terrain, skiing speed, poor visibility, crowded trails, and obstacles such as rocks and trees. According to Matthew Smith et al. [5], the most common injuries were to the lower extremity and the knee. Collisions can cause fractures and head trauma, while falls can result in fractures and sprains. When considering the use of an exoskeleton, it is essential to take into account the added weight of the device and the user, which could potentially cause more severe injuries in case of a collision. Furthermore, it is crucial to address the possibility of exoskeleton malfunction due to the use environment.

3 Reflection on specifications

Passive exoskeletons designed for alpine skiing rely on springs to absorb weight and release energy vertically, so they are not suitable for producing horizontal push. Currently, WIITE, a modified version of the TWIICE, is the best available option for skiing exoskeletons. It has been developed for ski touring, a type of alpine skiing where the skier climbs with non-slip soles and a free heel before descending as in regular alpine skiing. Although the exoskeleton is self-adapting, the user requires assistance to get into it. Demonstrations have shown a paraplegic user skiing with crutches and the help of someone walking beside them [6]. The current design connects the ski to the foot using alpine skiing rigid boots with a high upper fixed in three points to the exoskeleton and a connection to the ski at the end of the shoe. The absence of ankle flexion requires increased flexion in the knee and anteflexion of the body. It is unclear if the exoskeleton has a braking system. That said, there are still areas where exoskeleton technology needs to be improved, in order to create a more natural movement and increase the safety of the device. Firstly, the battery capacity needs to be increased to provide greater autonomy, and a thermistor should be added to maintain the battery temperature within safe levels. In terms of mechanical and biomechanical requirements, a thorough kinematics and kinetics analysis has shown that the joint between the skies and exoskeleton should obey simultaneously. Skiing requires the timed application of varied downward pressure forces for the push-off phase to maintain grip and absorb the ski's elasticity, followed by null to negative forces to release the grip and compensate for the ski's weight. Achieving this balance is necessary to maintain control and stability while skiing. In particular, as previously discussed in Section 2, it is necessary to size the exoskeleton motors to support a minimum of $700N$.

Ski and Exoskeleton Joint: A well-designed binding mechanism is essential for the exoskeleton to securely hold the user's foot in place and allow for efficient transfer of force from the foot to the ski. The binding mechanism should also enable easy release. Furthermore, it should be built with the necessary flexibility and range of motion to allow the user to move naturally. Considering the biomechanical requirements of cross-country skiing, the exoskeleton should allow for flexion in the heel and knee to a lesser degree, followed by plantar flexion and extension of the knee and hip. One option is the exoskeleton ski link (Fig.2-A), which minimizes torque-induced wounds by shunting the foot. The release system should be lightweight to avoid constraints during falls. Alternatively, a mechanical part can transfer force from the ski to the exoskeleton while allowing foot and ankle movement. Another option is a boot-based design (Fig. 2-B), where the mechanical link is via the boot avoiding having a specially designed ski, but the boot may have to bear both the weight of the body and exoskeleton in case of fall. In this context, the analysis of ski technique reveals that the diagonal style requires a specific angle between the right ski boot and ski, as indicated by Figure 1. This angle should be approximately 45° and gradually decrease until the 4th phase. The same applies to the left ski boot and ski. As regards the movement itself, as discussed in Section 2, the different phases of cross-country skiing movement are characterized by varying muscle activation. A study in [7] has shown that by collecting 3 linear acceleration components along the X, Y, and Z axes, as well as 3 angular acceleration components around those same axes from a single micro-sensor unit (IMU equipped by a GPS) located in the centre of the upper back, it is possible to identify cyclical move-

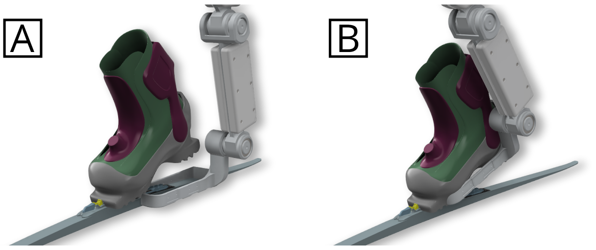

Figure 2: Sideways view of proposed binding mechanisms: exoskeleton ski link (A) and boot-based design (B).

ment patterns for the diagonal stride and double poling techniques. Integrating it into the exoskeleton control law so that it could automatically adjust the angle between the ski and ski boots and provide adequate support to the active motion of the user at each phase of the movement should be considered. We suspect that the more transparent the command, the easier the user, the less cognitive demand from the user, and the more attention is left for navigation and obstacle avoidance.

Braking phase: Cross-country skiing is performed in flat areas, so braking is accomplished by lowering step frequency. This is a consideration for adding a braking system to an exoskeleton. On modest slopes, users may need additional braking methods such as bending over and placing poles between their legs to create resistance. A dedicated stop system, like "stop-skis" in alpine skiing, could be added to the exoskeleton for emergency braking. However, it would require detecting the need to brake or providing a braking system that can be triggered by the user. Interaction design is important for the latter option. The exoskeleton must limit damage from external impacts and user collisions. It should also allow for quick release in case of falls or collisions to ensure user safety.

4 Conclusions

Rehabilitation exoskeletons can be modified to be suitable for cross-country skiing. WIITE by TWIICE seems to fulfil most of the requirements and to be a good starting point, but it has not yet been applied to cross-country skiing. It is important to note that cross-country ski exoskeletons are still at the stage of brainstorming, and it is difficult to make accurate predictions about the future of this technology. Nonetheless, there is space for further adaptations and improvements to enhance the performance, safety, and accessibility of exoskeleton technology for cross-country skiing. Possible developments we can see are haptic training platforms including exoskeleton technologies or improved sport accessibility for disabled persons. These developments will have the opportunity to provide secure practice, provided they include the safety aspects from the start. In any case, testing with different scenarios would be required to find a solution that copes with falls without breaking the skis or harming the user if this preliminary idea comes to the stage of proof of concept.

Conflict of interest: The authors declare no conflict of interest.

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