

BIOMECHANICAL COMPARISON OF PIN AND FREERIDE SKI MOUNTAINEERING
BINDINGS IN RECREATIONAL SKIERS

by

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ABSTRACT

Previous studies on competitive ski mountaineering have shown that increasing equipment weight increases metabolic cost of the skier. However, whether differences in weight influence the kinematics or efficiency of uphill skinning in recreational skiers remains unknown. Therefore, the purpose of this study was to compare the lower body kinematics and mechanical efficiency of uphill skinning between these bindings in recreational skiers. Sixteen skiers skinned on a treadmill on matching skis with pin or freeride bindings, for three-minute stages at grades of 8% or 15% while kinematics and heart rate were recorded over the final thirty seconds. A walking graded exercise test was performed to estimate oxygen consumption and respiratory exchange ratio from heart rate during the skinning protocol, for calculation of aerobic metabolic rate. Sagittal plane joint angles of the lower limb and torso, cycle metrics, vertical power, aerobic metabolic rate, and mechanical efficiency were all compared for each condition parametric mapping or linear mixed effect models. Results showed that in the freeride binding, compared to the pin, there was slightly greater ankle plantarflexion ($p=.05$), knee flexion ($p=.02$), and hip flexion ($p=.05$) around toe-off. However, these differences were no more than 2° of joint motion, and isolated to a small area of the gait cycle. Differences in cycle metrics were also found between the bindings, with slower cycle rates ($p<.001$, $d=0.34$), longer cycle lengths ($p<.001$, $d=0.36$), cycle time ($p<.001$, $d=0.36$), and higher step heights ($p<.001$, $d=0.32$) in the freeride binding. While statistically significant, these differences were small in magnitude and effect size. Supporting that differences in kinematics were likely negligible, our results found no significant differences in vertical power ($p=.69$), aerobic metabolic rate ($p=.61$), or mechanical efficiency ($p=.81$) between bindings. Collectively our results show that in laboratory settings at the grades tested, there is no difference between a pin and freeride binding that are relevant for recreational skier uphill movement or efficiency.

CHAPTER ONE

INTRODUCTION

Ski mountaineering, or skimo, is one of the fastest growing winter activities in the United States, with the total number of participants expected to triple to 2.2 million people from 2019 to 2023¹. The increase in popularity has also resulted in an increase in equipment sales, with skimo specific equipment estimated to be an eleven-billion-dollar industry by 2032², making it the fastest growing segment of the skiing industry. Skimo is popular for both recreational and competitive populations³, however the equipment used by these populations looks very different. A key reason for these differences is that recreational skimo participants tend to prioritize the downhill portion of the activity⁴, and tend to choose equipment designed for downhill performance and safety. While high level skimo racing is an extreme endurance activity, and therefore any excess weight carried by the athlete is proven to be detrimental to performance⁵⁻⁸.

An early pioneer in ski mountaineering was a Norwegian skier, Sondre Norheim, who developed the first telemark binding around 1868⁹. The development of the telemark binding eventually led to the development of the modern ski mountaineering binding. Most modern bindings and boots designed for skimo connect the binding to the boot using specialized pin inserts for uphill travel, allowing free rotation of the boot and ski about the toe. Combined with specialized boots that provide free ankle hinging and highly adhesive unidirectional skins, skiers can ascend snowy terrain using a natural walking like movement, referred to as skinning. During the downhill travel, the ankle pivot mechanism of the boot becomes rigid, and the heel binding locks the boot to the ski.

Several studies have shown that increasing binding or boot weight significantly increases energetic cost to the athlete⁵⁻⁸. As a result, almost all skimo racers use a pin binding design³. These bindings have pins at the toe, held in place by retention springs which clamp them into specialized inserts in the boot toe¹⁰. The heel binding rotates so two pins protrude forward into specialized slots in the heel of the boot, thus locking the boot to the ski for downhill travel. While lightweight, several studies have shown that pin bindings do not always meet the International Organization for Standardization standard¹¹ for either alpine skiing or skimo bindings^{10,12}, often requiring greater torsional forces to generate a release from the binding.

The increased torsional release forces in pin bindings raise concerns regarding injury while skiing in these bindings^{12,13}, especially when skiing in bounds at ski resorts. As a result, many skiers want a binding that can accomplish both skimo and in-bounds resort skiing, with the safety factors that are required for typical alpine ski bindings. Thus, many options for skimo bindings exist on the market, such as adapter bindings, frame bindings, hybrid freeride bindings, and pin bindings. Each binding style has advantages and disadvantages, such as cost, weight, and safety features, leaving the recreational participant many options on what to purchase. Hybrid freeride bindings are an appealing option for recreational skiers, as these bindings are heavier and fully enclose both toe and heel of the boot, like an alpine binding for downhill skiing, and transition to pin inserts at the toe with a releasable heel for uphill travel, bridging the gap between heavy frame bindings and pin bindings. Whether the increased mass of these bindings is enough to influence the efficiency and energetic cost of uphill travel, especially in recreational skiers, remains unknown.

Any differences in efficiency and energetic cost between pin and freeride bindings would likely be accompanied by changes in skinning biomechanics. However, to date relatively little is known about the biomechanics of uphill skinning or how equipment may influence these mechanics. Previous studies on skimo bindings have examined retention/release characteristics¹² and relationship to knee injury¹⁰, while others have examined how binding riser height influences skinning biomechanics and physiology^{14,15}. However, no studies have examined whether changes in equipment weight affect biomechanics of skinning. This could be especially relevant when considering weight differences between pin and freeride bindings as the additional mass is located at the end of the kinetic chain, thus having a larger impact on movement or efficiency.

Additionally, previous studies on how equipment weight effects energetic cost of skimo did not include multiple slope angles in their experimental design⁵⁻⁸, which may be a limitation, as slope gradient has shown to influence other aspects of locomotion. Skimo research on the effects of heel riser height and slope gradient on biomechanical and physiological variables have demonstrated the importance of studying changes in equipment across multiple slopes^{14,15}, as the effect of riser height on energy cost depended on the slope angle. In another study, cycle metrics, energy cost, and efficiency in competitive skimo athletes changed significantly with varying speed and slope angle^{16,17}. The importance of considering slope angles within the methodology of locomotion research is further supported by previous walking gait with changing grades^{18,19}.

The gap in knowledge on how binding weight affects recreational skier biomechanics and physiology across multiple grades and speeds should be addressed to provide recreational skiers with more information for choosing ski bindings. Therefore, the purpose of this study was to compare lower body joint angles, cycle metrics, and energetic demands during uphill skinning

with pin and free ride bindings at two slope gradients in a recreational skier population. We had three hypotheses: H1) there would be greater ankle, knee, and hip range of motion in the freeride binding across both grades, H2) slower cycle rates, longer cycle lengths, and lower step heights in the FR binding across grades, and H3) compared to the pin binding, there would higher vertical power output and metabolic rate, resulting in no change in mechanical efficiency in the freeride binding across grades. In this paper, Chapter Two provides a review of literature relating to recreational exercise, ski mountaineering, and previous research on ski mountaineering. Chapter Three comprises a research study to answer the following question and hypothesis. Chapter Four provides future directions related to this research question.

Research Question

How does the weight difference between a pin and freeride ski mountaineering binding affect the kinematics and efficiency of a recreational skier during uphill travel?

Hypothesis

There would be greater ankle, knee, and hip range of motion, slower cycle rates, longer cycle lengths, lower step heights, higher vertical power output, and higher metabolic rate in the FR binding across grades.

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CHAPTER TWO

LITERATURE REVIEW

Recreational Exercise and Its Positive Effect on Health

It has long been known that physical activity is an extremely important factor to a healthy life. The opposite is true as well, physical inactivity is associated with the development of around forty non-communicable diseases, such as cardiovascular disease (CVD) and type II diabetes¹. A large body of epidemiological studies over the last several decades highlight the importance of regular physical activity for disease prevention and decreasing risk of mortality²⁻⁴. Regular physical activity has been shown to have economic benefits as well, decreasing the cost of health insurance, health care, and lost wages due to poor health^{5,6}. Exercise is important for maintaining body function with age, preserving movement ability throughout life. Studies on populations of lifelong aerobic exercisers show higher muscle mass and better muscle function compared to sedentary people, both in terms of mitochondrial and motor unit density, as well as muscle repairability⁷.

In addition to physical health, exercise is extremely important for mental health⁸. For example, the incidence of depression has been directly linked to the sedentary behavior and lack of exercise⁹. Alzheimer's disease risk is increased by type II diabetes, a very common co-morbidity in sedentary populations^{2,9}. Additionally, exercising in outdoor spaces can increase the mental health benefits of exercise^{3,10}. The multi-study analysis from Barton and Pretty¹¹ found a large dose-response relationship between exercising outdoors, particularly in mountainous environments, with improvements in self-esteem and mood.

Exercising in high altitude mountainous terrain, or alpine exercise, has been shown to have increased benefits for health, as compared to other forms of recreating. Mountaineering and uphill walking at altitudes have been shown to require a greater metabolic output, increasing the intensity of activity and thereby increasing the benefit of the session¹². For public health, providing people with green spaces and places to recreate outdoors has been shown to decrease obesity rates and stress in urban areas¹³.

Health Promotion Strategies

One issue with getting people physically active is simply getting them to regularly take time for exercise¹⁴. Numerous studies have shown that increasing daily physical activity time has significant positive impacts on both individual health, and the decreases the economic burden of health complications due to inactivity⁴⁻⁶. However, in a rather large survey-based study, only 59% of respondents exercised within the recommended durations for health benefits¹⁴.

An important aspect of increasing daily activity levels in adults is the modality/formality of exercise^{4,14,15}. In the meta-analysis by Sofi et al¹⁵, work or occupational based physical activity rates have decreased in recent years, while leisure time physical activity rates have been increasing. Targeting adults with modalities of exercise that are fun to take part in during leisure time is an effective way to increase physical activity time in adults. In another survey-based population study, it was found that high levels of enjoyment of exercise modality were highly correlated with high amounts of time spent exercising¹⁶. Another study comparing an intervention group of exercisers (offered exercise programs including aquatics, dance, and Nordic walking) and a control (only given information about local gyms) it was found that in quarterly checkups that exercise enjoyment levels were much higher in the intervention group. In

addition, the type of exercise (i.e. Nordic walking versus running) was highly correlated with the amount of time spent performing exercise, and the likelihood of returning to activity¹⁷.

Another barrier to regular exercise is maintaining activity during the winter months¹⁸. Merchant et al¹⁸ found that in a Canadian population, where climatic variation between summer and winter is extreme, people were 86% more likely to participate in leisure-time physical activity in the summer versus the winter. Significant correlations have been shown between weather conditions (i.e. warm-dry climates versus cold-moist climates) and the amount of time spent physically active in the United States¹⁹. Thus, recreational activities that can be performed during winter months and are fun and engaging to participate in should be focused on as a means to increase physical activity time during the winter.

Ski mountaineering (skimo) is a may be a good option for people seeking outdoor recreation in the winter, as it requires a higher aerobic intensity compared to level ground walking or running²⁰. Recreationally, people tend to participate in skimo because they are seeking recreation and health benefits, it is fun to do, and they get to exercise in the mountains in the winter²¹. Additionally, skimo is a great option for those who enjoy alpine, or downhill, skiing, but seek to escape cluttered lift lines at resorts but still get access to enjoyable downhill terrain. As alpine skiing assisted by mechanical lifts gets more expensive and less accessible, skimo participation in the United States has been rapidly increasing in popularity²².

Ski Mountaineering

Historians estimate that skis have been used by ancient civilizations for transportation across snow and ice for thousands of years²³. The earliest well-preserved skis were discovered in central Norway and estimated to be from the seventh century. Ancient skis were made from

wooden planks and used animal skins or fish scales to provide unidirectional friction for pushing, with some form of animal fat or oils to assist with gliding along the snow. These skis were typically required for winter travel and hunting. An early pioneer in ski mountaineering was a Norwegian skier, Sondre Norheim, who developed the first telemark binding around 1868²⁴. The development of the telemark eventually led to the development of the modern ski mountaineering binding, allowing free heel movement, while the boot attaches to the ski at the toe, and can rotate upwards to allow easier uphill travel.

Organized ski races began in the early 18th century, but ski mountaineering was not officially an Olympic event until the 1924 Winter Olympic Games Chamonix, France. However, it was removed fourteen years later due to several avalanche deaths^{25,26}. More recently, the International Ski Mountaineering Federation (ISMF), the regulatory organization for competitive ski mountaineering, became officially recognized by the International Olympic Committee in 2016. Skimo then appeared in the 2020 Youth Winter Olympic Games²⁵. The sport will now be included in the 2026 Milano-Cortina Winter Olympic Games for the first time since 1938. Skimo is a rapidly growing winter activity in the past decade, with total number of participants in the U.S. alone tripling to 2.2 million people from 2019 to 2023²². Combined with the inclusion of skimo in the Olympics once again, there has been a large increase in the number of research studies examining various aspects of skimo, however research in this area is still relatively scarce²⁷.

Recreational vs Competitive Ski Mountaineering

As was stated previously, skimo is not only a highly competitive endurance racing sport, but a very popular winter recreation activity. Recreationally, people participate in skimo in a

variety of settings, from groomed slopes at resorts that allow uphill travel, as opposed to lift served skiing, in off-piste conditions in the side-country of resorts, and in backcountry conditions²¹. In addition to the large increases in participation statistics over the last few decades, sales of skimo equipment is quickly expanding with a market value estimated to be an \$11 billion industry by 2032²⁸. Due to the rapid increase in demand for skimo equipment, research in this area has increased over the last decade, with much of the research focusing on retention-release values of skimo bindings²⁹⁻³¹, equipment weight and energy cost³²⁻³⁵, or the effect of using heel risers on biomechanics and physiology^{36,37}. However, as was mentioned research in this activity is still relatively scarce, and research that has been performed primarily focuses on competitive skimo racing, not the recreational participant.

A key difference between recreational and competitive skimo populations is the equipment used, more specifically the weight of equipment. Because of the high aerobic demand of competitive skimo, success in the sport mainly revolves around the speed and duration able to be maintained at high aerobic intensities ($> 90\%$ of $\dot{V}O_2$ max). Thus, a critical component to the equipment used by competitive skimo athletes is weight²⁷. Lighter equipment improves racing performance, as less mechanical work against gravity needs to be performed on each stride, preserving more energy for higher speeds across long race durations. While lightweight equipment is beneficial for racing performance, several studies have shown that the extreme lightweight pin bindings do not always meet the standard set by the International Organization for Standardization standard³⁸ for either alpine skiing or skimo bindings^{31,39}, often requiring greater torsional forces to generate a release from the binding.

The increased torsional release forces that are observed in pin bindings raise concerns regarding injury while skiing in these bindings^{30,31}, especially for those skiers exploring larger terrain in the backcountry, farther from rescue services. As a result, many skiers want a binding that can accomplish both uphill skinning and secure downhill skiing, with the safety factors that are required for typical alpine ski bindings. Addressing this gap, ski companies have created hybrid freeride bindings. These bindings are heavier and fully enclose both toe and heel of the boot, similar to an alpine binding with safety features associated with typical downhill bindings^{38,40}. Hybrid bindings still transition to pin inserts at the toe with a releasable heel for uphill travel, like a pin binding. No studies have examined differences between hybrid freeride bindings and other popular skimo bindings to date.

Binding Design – Alpine vs Skimo

In the early 1800's, skiing technology involved leather lace up boots attached to long wooden skis with leather straps, allowing alpine skiing, however also leading to a high risk of injury⁴¹. As alpine skiing gained significant popularity in the early 20th century, metal releasable bindings were developed around 1940 to reduce injury risk, however they had little impact on the high rate of injuries to the lower limb.

Around 1960, the invention of plastic shelled ski boots allowed for a slightly safer binding-boot system, reducing the rate of ankle sprains and fractures, and allowing for better control of the ski⁴². Coincidentally, the invention of the plastic boot brought on new injury risks. As skiers had more control over the ski, they could reach higher speeds and carved turns, leading to a much higher prevalences of tibia-fibula fractures. In the event of a crash where the ski remains

fixed to the boot, the hard boot shell and long lever of the ski leads to high amounts of torque to the tibia and fibula, a perfect scenario for a lower leg injury³⁹.

In response, alpine bindings with retention and release settings were developed in the early 1970's with the aim to reduce the incidence of tibia-fibula fractures in alpine skiing⁴². The retention-release value is determined by skier weight, ability, age, and gender⁴³. Retention-release values were originally standardized by the Deutsches Institut für Normung (DIN), which is now a common slang term used to describe the number associated with a binding's retention-release value. Significant decreases in the incidence of lower leg fractures was observed in the following 30 years^{44,45}. These settings still exist in modern alpine binding design, and are regulated by the International Organization for Standardization^{38,40}, but are colloquially referred to as a 'DIN' setting. Since 1972, there has been a net reduction of 87% of twisting related lower leg injuries⁴⁶.

After the invention of the telemark binding further development of ski mountaineering bindings occurred throughout the 18th century²⁴. However, it wasn't until around 1950 that any major breakthroughs in the ski mountaineering bindings occurred, with the development of an underfoot plate added to cable style bindings for telemark skiing⁴⁷. The Tyrolia Tour binding was developed in 1959, a very crude method for creating a forward release mode for downhill skiing, and allowing free heel movement for uphill travel. In the 1970s, the Ramer Model R was invented, the first touring binding with a heel lift setting for uphill travel, however it still lacked any twist-release ability.

The 1980's brought the invention of adapter bindings, the Secura-Fix, that snapped into regular alpine bindings for uphill travel and could be removed for downhill travel. These styles

of touring adapters still exist, such as the modern Daymaker binding, shown in figure 1. However, these adapter bindings are very heavy and have a large stack height, or the distance from the ground to the boot attachment point. The invention of the pin binding came in the 1980's as well, with the skier Fritz Barthel inventing the first pin binding, which he patented in 1983⁴⁸. He later partnered with Dynafit in 1989 to begin manufacturing the flagship pin bindings which revolutionized ski mountaineering. As has been covered previously, these bindings are extremely lightweight, however often lack DIN settings that are common in alpine bindings.

More recently, the ISO³⁸ standards for retention-release values have been set for pin bindings, however numerous research studies have shown that pin bindings do not always meet these standards, depending on impact circumstances²⁹⁻³¹. As a result of these limitations, a multitude of binding styles exist on the market to meet the varying demands of the ski mountaineering population, shown in figure 1. Each binding style has advantages and disadvantages, such as cost, weight, and safety features, leaving the recreational participant many options on what to purchase.



Figure 1. Examples of common binding options for ski mountaineering. A) Alpine binding with DIN settings, must be used with binding B for uphill travel, B) Adapter binding being used in an alpine binding for uphill travel, C) Frame touring binding, entire binding attaches to toe and heel for uphill and downhill travel, D) Pin binding, E) CAST binding with interchangeable toe piece (pin toe piece for uphill, frame toe piece for downhill), F) Freeride hybrid binding, toe piece mechanism moves to expose ‘pins’ for uphill travel, and closes to enclose the toe in a frame style for downhill travel with DIN settings.

Ski Mountaineering Research Background

Two research studies on equipment weight in elite skimo competition have shown a clear increase in energetic cost with relatively small increases in artificially added weight to the boots^{32,35}. Tosi et al³⁵ used weighted bands of 0.5, 1.0, and 1.5 kg added to the ankle of the ski boot during 500 meter ski trials on snow. They found that an addition of 1.0 kg of weight resulted in a 2% increase in energetic cost to the athlete. The researchers also developed an equation to theoretically determine the percent increase in energetic cost based on percent of

total body weight being added to the athlete, % Energy cost = 1.71 x % Weight. Another study by Bortolan et al³² examined a similar research question, however this study added smaller increments of weighted bars (0.2 kg) to the lower foot of the athletes in a controlled laboratory setting. Slightly different from the results of the previous study, this study found that for every 0.2 kg added, the energy cost increased by 1-2%, a larger change in cost for less weight being added.

Two other research studies examined how changing equipment design, ski binding type and boot type, affected the mechanical energy and energy cost of the ski mountaineer^{33,34}. Before summarizing the results of these studies, it must be noted that both studies examined differences between a pin style binding and a frame style touring binding. As shown in figure 1, frame bindings must remain fixed to the toe and heel of the boot in both uphill and downhill travel, meaning that the skier must lift the mass of the boot and entire binding from the ski on every step. In contrast, other popular bindings (Pin, Freeride, Cast) have a separated heel and toe piece, allowing the boot to hinge at the toe, while the weight of the heel piece remained on the ski for every step. While no studies have examined the biomechanics of a pin, freeride, and frame style binding, it would be hypothesized that the spatiotemporal variables and kinematics of the ankle and knee may be altered by the differences in attachment style between a pin/freeride and frame binding.

Schwameder et al³³ found very large differences in the mechanical energy required to move the ski/binding system between the frame and pin style bindings. They concluded a roughly 72% to 88% change in mechanical energy between the two frame bindings and the pin binding. As expected, this resulted in significant increases in the metabolic cost of skinning.

Skinner et al³⁴ similarly found that the frame binding increased mechanical energy, oxygen consumption, and energy cost compared to an extremely lightweight racing style pin binding ski setup. Their results showed an 18% increase in energy cost in this condition. This increase in energy cost contrasts the theoretical equation proposed by Tosi et al³⁵, which predicted the energy cost due to the increase in percent weight to be only 5%. This suggests that factors other than equipment weight alone, such as changes in biomechanics due to the binding attachment style, treadmill skinning speed, or grade, must be considered in future studies researching skimo equipment design.

The effect of heel riser height and slope gradient on biomechanical and physiological variables has also been researched previously^{36,37}. On modern skimo bindings, heel risers can be used to make skinning more comfortable as slope gradient increases. These studies demonstrated the importance of studying changes in equipment across multiple slopes as sagittal plane joint angles and step length showed a main effect of riser height and gradient individually, however there was an interaction effect between riser height and gradient and energy cost. At a lower grade, energy cost was different between riser heights, however at steeper grades the effect of riser height on energy cost did not exist.

Mechanical Efficiency

Mechanical efficiency is a measure commonly calculated to assess the ratio between power produced and metabolic rate. The theory behind mechanical efficiency was originally developed by Margaria et al⁴⁹ to describe the relationship between running speed and energy cost in trained and untrained runners. The definitions developed in this study were further used by Margaria to compare the energy cost and efficiency of running compared to walking⁵⁰. This

definition of mechanical efficiency only considers the rise and fall of potential energy as the main contributor of energy expenditure, disregarding kinetic energy, as it can be assumed that at high slope angles the main contributor to mechanical external work is the the vertical displacement of the center of mass⁵⁰⁻⁵².

In the context of skiing, studies have examined cross-country sprint skiing efficiency⁵³, laboratory-based factors that predict performance in biathlon⁵⁴, and energy cost and efficiency of skimo at multiple grades and speeds⁵⁵. The study by Laakonsen et al⁵⁴ also defines methodology to determine the necessary inputs for calculation of mechanical efficiency in the context of laboratory based treadmill skiing, once again assuming the main contributor to external mechanical work is the vertical displacement of the center of mass for each step, which can be calculated based upon subject mass, treadmill gradient, and treadmill speed, as shown in equation 1. It should be noted that Laaksonen et al⁵⁴ also included the energy required to overcome rolling resistance on roller skis, which does not need to be taken into account for skimo gait.

$$\text{vertical mechanical power [W]} = m \cdot g \cdot \sin(\arctan(\theta)) \cdot v \quad (1)$$

Where m is the mass of the participant including all equipment carried during the test (kg), g is gravity (9.81 m/s^2), θ is the treadmill slope ($^\circ$), and v is the belt speed of treadmill (m/s).

Aerobic metabolic rate can be calculated similar to Praz et al⁵⁵ and Laaksonen et al⁵⁴ using $\dot{V}O_2$ (L/min) and RER, when values are ≤ 1.0 , of the subject, which is shown in equation 2:

$$\text{aerobic metabolic rate [W]} = (4184(\dot{V}O_2 (1.1RER + 3.9)))/60 \quad (2)$$

Finally, mechanical efficiency can be calculated as the ratio of vertical mechanical power and aerobic metabolic rate^{50,53–55}, shown in equation 3:

$$\text{mechanical efficiency [\%]} = 100 \cdot \frac{\text{vertical mechanical power}}{\text{net metabolic rate}} \quad (3)$$

The definition of mechanical efficiency has been used in previous skimo research, and can be used to compare differences in energy cost and efficiency of different skimo equipment.

Gaps in Knowledge

As research in ski mountaineering is relatively scarce, there are several gaps in the literature that should be addressed in future research. To date, very few research studies have considered the biomechanics of ski mountaineering. Praz et al^{51,55} considered how spatiotemporal variables are affected by slopes and speeds. The prior mentioned research by Lasshofer et al^{36,37} examined the effect of heel riser height and slope angle on sagittal plane joint kinematics, spatiotemporal variables, and muscle activity. Therefore, it is important to consider the biomechanics of skimo in future research methodology, as more background information on this is need to develop foundational knowledge of what typical skimo movement is. Another gap in knowledge is how skimo gait changes from laboratory studies to on-snow practice. No previous research has directly examined this concept, however the work by Praz et al^{51,55} did find that spatiotemporal changes with slopes and speeds were consistent between the snow and treadmill.

A rather large gap in skimo research is the population of interest. Almost all prior research discussed in this review has examined the competitive skimo racer. However, as has been highlighted the equipment used, exercise intensity, and goals of the participant change dramatically from recreational to competitive populations. The safety factors of equipment used

has been examined²⁹⁻³¹. However, many other factors of recreational skiers should be considered, such as how the participant interacts and chooses equipment or characteristics of a typical mountaineering population (i.e. fitness, touring pace, kilometers of ascent a season, average injury rate, etc.) should be considered for future research studies.

Conclusion

A large body of literature has displayed the negative impacts of physical inactivity. A major challenge to increasing physical activity in the general public is finding exercise modalities that are enjoyable, as it increases the likelihood of returning to activity. Another challenge is finding ways to encourage exercise in winter months. Prior research has also shown that alpine exercise has many benefits in terms of physical and mental health benefits. Ski mountaineering is an increasingly popular form of winter recreation, as it is an enjoyable form of alpine exercise that can be performed in the winter. While previous research on skimo has examined important aspects such as equipment safety features and energy cost, most research has neglected the recreational participant. Further research into the equipment used by recreational participants should be examined in order to aid skiers' knowledge on the equipment's advantages and disadvantages as the activity increases with rapid popularity.

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CHAPTER THREE

BIOMECHANICAL COMPARISON OF PIN AND FREERIDE
SKI MOUNTAINEERING BINDINGS IN RECREATIONAL
SKIERS

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**Biomechanical Comparison of Pin and Freeride Ski Mountaineering Bindings in
Recreational Skiers**

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Abstract

Previous studies on competitive ski mountaineering have shown that increasing equipment weight increases metabolic cost of the skier. However, whether differences in weight influence the kinematics or efficiency of uphill skinning in recreational skiers remains unknown. Therefore, the purpose of this study was to compare the lower body kinematics and mechanical efficiency of uphill skinning between these bindings in recreational skiers. Sixteen skiers skinned on a treadmill on matching skis with pin or freeride bindings, for three-minute stages at grades of 8% or 15% while kinematics and heart rate were recorded over the final thirty seconds. A walking graded exercise test was performed to estimate oxygen consumption and respiratory exchange ratio from heart rate during the skinning protocol, for calculation of aerobic metabolic rate. Sagittal plane joint angles of the lower limb and torso, cycle metrics, vertical power, aerobic metabolic rate, and mechanical efficiency were all compared for each condition parametric mapping or linear mixed effect models. Results showed that in the freeride binding, compared to the pin, there was slightly greater ankle plantarflexion ($p=.05$), knee flexion ($p=.02$), and hip flexion ($p=.05$) around toe-off. However, these differences were no more than 2° of joint motion, and isolated to a small area of the gait cycle. Differences in cycle metrics were also found between the bindings, with slower cycle rates ($p<.001$, $d=0.34$), longer cycle lengths ($p<.001$, $d=0.36$), cycle time ($p<.001$, $d=0.36$), and higher step heights ($p<.001$, $d=0.32$) in the freeride binding. While statistically significant, these differences were small in magnitude and effect size. Supporting that differences in kinematics were likely negligible, our results found no significant differences in vertical power ($p=.69$), aerobic metabolic rate ($p=.61$), or mechanical efficiency ($p=.81$) between bindings. Collectively our results show that in laboratory settings at the grades

tested, there is no difference between a pin and freeride binding that are relevant for recreational skier uphill movement or efficiency.

Introduction

Ski mountaineering (skimo) is one of the fastest growing winter activities in the United States, with the total number of participants expected to triple to 2.2 million people from 2019 to 2023¹. The increase in popularity has also resulted in an increase in equipment sales, with skimo specific equipment estimated to be an eleven-billion-dollar industry by 2032², making it the fastest growing segment of the skiing industry. Skimo is popular for both recreational and competitive populations³. Recreationally, participants may partake in skimo to escape cluttered lift-lines at resorts, exercise in the mountains through the winter, and explore new terrain in the backcountry⁴. From a competitive perspective, skimo is a highly competitive sport which will make its Olympic debut in the 2026 Milano-Cortina Winter Olympics³.

Equipment designed for skimo racing is designed with the priority of minimizing weight in order to maximize uphill performance. Several studies have shown that increasing binding or boot weight significantly increases energetic cost to the athlete⁵⁻⁸. As a result, almost all skimo racers use an ultralightweight pin binding design³. These bindings have pins at the toe, held in place by retention springs which clamp them into specialized inserts in the boot toe⁹. This allows free hinging of the boot and ski at the toe, which combined with specialized boots that provide free ankle rotation, allow a natural walking like movement during uphill travel, referred to as skinning. During downhill skiing, the ankle of the boot locks to become rigid and the heel binding rotates so two pins protrude forward into specialized slots in the heel of the boot, thus locking the boot to the ski. While lightweight, several studies have shown that pin bindings do

not always meet the International Organization for Standardization standards for retention-release values for either alpine skiing or skimo bindings^{9, 10, 11}, often requiring greater torsional forces to generate a release from the binding.

The increased torsional release forces in pin bindings raise concerns regarding injury while skiing in these bindings^{11,12}, especially in bounds at ski resorts. As a result, many skiers want a binding that can accomplish both skimo and in-bounds resort skiing, with the safety factors that are required for typical alpine ski bindings. This might be especially true for recreational skiers who may prioritize the downhill skiing experience in the backcountry. To address this gap, ski companies have created hybrid freeride bindings. These bindings are heavier and fully enclose both toe and heel of the boot, like an alpine binding, for downhill skiing, and transition to pin inserts at the toe with a releasable heel for uphill travel. Whether the increased mass of these bindings is enough to influence the efficiency and energetic cost of uphill travel, especially in recreational skiers, remains unknown.

Any differences in efficiency and energetic cost between pin and freeride bindings would likely be accompanied by changes in skinning biomechanics. However, to date relatively little is known about the biomechanics of uphill skinning or how equipment may influence these mechanics. Previous studies on skimo bindings have examined retention/release characteristics¹¹ and relationship to knee injury⁹, while others have examined how binding riser height influences skinning biomechanics and physiology^{13,14}. However, these studies did not examine if changes in equipment weight affect biomechanics of the movement. This could be especially relevant when considering weight differences between pin and freeride bindings as the additional mass is located at the end of the kinetic chain, thus having a larger impact on movement or efficiency.

Previous studies on how equipment weight effects energetic cost of skimo did not include multiple slope angles in their experimental design⁵⁻⁸, which may be a limitation, as slope gradient has shown to influence other aspects of locomotion. Skimo research on the effects of heel riser height and slope gradient on biomechanical and physiological variables have demonstrated the importance of studying changes in equipment across multiple slopes^{13,14}. Sagittal plane joint angles and step length showed a main effect of riser height and gradient. However, there was an interaction effect between riser height and gradient on energy cost. At a lower grade, energy cost was different between riser heights, however at steeper grades the effect of riser height on energy cost did not exist. Additionally, Praz et al^{15,16} reported that cycle metrics, energy cost, and efficiency in competitive skimo athletes change significantly with varying speed and slope angle. The importance of considering slope angles within the methodology of locomotion research is further supported by previous walking gait studies^{17,18}.

Therefore, the purpose of this study was to compare lower body joint angles, cycle metrics, and energetic demands during uphill skinning with pin and free ride bindings at two slope gradients in a recreational skier population. We had three hypotheses: H1) there would be greater ankle, knee, and hip range of motion in the FR binding across both grades, H2) slower cycle rates, longer cycle lengths, and lower step heights in the FR binding across grades, and H3) higher vertical power output and metabolic rate with no change in mechanical efficiency in the FR binding across grades.

Methods

Participants

Sixteen skiers (sex: 8M/8F; age: 21 ± 1.48 yrs, height: 1.81 ± 0.06 m, mass: 78.1 ± 7.25 kg) participated in this study. Inclusion criteria for this study were: at least two-years of skimo experience, no history of lower extremity injury in the past two years, and a boot sole length which would fit the research skis used in the study (262-288 mm for shorter skis or 295-325 mm for longer skis). All participants provided written informed consent and the protocols for this study were approved by the Montana State University Institutional Review Board under protocol 1126.

Experimental Design

All testing was completed during a single visit to the laboratory. Prior to beginning the treadmill skinning protocol, participant height and total mass, wearing all research equipment, clothing, and ski equipment (boots, poles, and each set of skis separately) was recorded using an integrated beam scale and stadiometer (Health-O-Meter, Continental Scale Corp., Bridgeview, IL, USA). Participants then performed a five-minute warmup skinning on a ski treadmill. Following the warmup participants completed three-minute bouts using matching skis, mounted with either the Backland Tour pin (P) or the Shift 13MN freeride (FR) bindings. Both bindings were manufactured by Atomic (Atomic Austria GmbH, Altenmarkt, Austria) and had masses of 398 g and 880 g, respectively for a single binding. For each binding type tested, skinning trials were performed at 8% at 1.1 m/s and 15% at both 0.63 m/s and 1.1 m/s. Two speeds were used at the higher grades to have conditions with matched speeds and matched relative intensities across the grades, as previous skimo studies have shown that mechanical efficiency is dependent on

both grade and speed^{6,16,19}. The speed for the matched relative intensities was determined by calculating the speed which would result in similar vertical power output between 8% and 15% grades. This would also then leave any differences in mechanical efficiency as being solely due to changes in the metabolic rate.

The order of bindings, grades, and speeds were quasi-randomized across participants where participants either received the P or FR binding first and started with either the 8% or 15% grades, and if at 15% then with either the matched speed or matched relative intensity. To minimize the number of ski changes, all three stages in one binding were completed before changing to the other binding type. All trials were performed using participants own boots and poles but on laboratory provide skis mounted with either the P or FR bindings. For each binding type, two lengths of skis were used depending on participants boot sole length (long: 179cm, Backland 85 UL, short: 165cm, Backland 86 SL, Atomic Austria GmbH, Altenmarkt, Austria). Torso and lower body kinematics and heart rate were recorded during the last thirty seconds of each stage of the treadmill skinning protocol.

After completion of the skinning protocol participants were provided a ten-minute rest after which they completed a modified Balke walking graded exercise test²⁰, for the purpose of estimating the rate of oxygen consumption ($\dot{V}O_2$) and respiratory exchange ratio (RER) from heart rate (HR) during the treadmill skinning protocol. The test started at 0% incline and a speed of 4.8 kph for females, and 5.3 kph for males. Every three minutes, the treadmill grade increased by 2.5%, until the treadmill reached 15% grade where speed began to increase by 0.8 kph per stage. Participants were informed of the testing protocol and test termination criteria prior to testing. The test was terminated when the participant grabbed or stepped off the treadmill,

indicating they were maximally exhausted and the following criteria were met, 1) RER values exceeded 1.0 when averaged over thirty seconds, 2) heart rate was above 90% of age predicted maximum when averaged over 30 seconds²¹.

Instrumentation

The treadmill skinning protocol was performed on an oversized ski treadmill (belt dimensions: 2.5 x 3 m, Fitnex Fitness Equipment Inc., Dallas, TX, USA). Whole body kinematics were recorded using a 6-camera motion capture system (Motion Analysis Corp, Rohnert Park, CA) sampling at 120 Hz. Forty retroreflective markers were placed on the torso, pelvis, and lower extremities to create an 8-segment biomechanical model. Markers used to derive anatomic coordinate systems were placed bilaterally on the acromion, anterior and posterior superior iliac spines, medial and lateral femoral epicondyles, medial and lateral boot hinge points, and mid-toe of boot. Rigid clusters with four non-colinear tracking markers were securely attached to the thigh and shank segments using elastic wrap. Additional tracking markers were placed on the xiphoid process of the sternum, 7th cervical vertebra, iliac crests, approximate base of the 5th metatarsals (crest of lateral boot curve), heel in-line with the toe marker. Markers used to track ski kinematics were placed on the medial and lateral edges of the ski tips, in front of toe piece, behind heel piece, and on ski tail, and markers placed on the treadmill corners defined the treadmill belt as a segment.

The walking graded exercise test was conducted on a Woodway 4FRNT fitness treadmill (belt dimensions: 0.9 x 1.8 m, Woodway USA Inc., Foster, CT). Oxygen consumption and expiration was collected via two-way Rudolph valve mask and nose clip, and recorded using a ParvoMedics TrueOne 2400 metabolic cart (ParvoMedics, Salt Lake City UT, USA) with 4-Liter

high efficiency mixing chamber. The system was given one hour to warm up and was calibrated following manufacturer instructions prior to each use. Heart rate was recorded synchronously with the metabolic cart via a Polar H10 heart rate sensor (Polar Electro Oy, Kempele, Finland). In mixing chamber mode, $\dot{V}O_2$ (L/min) and RER were recorded in 30 second averages across the entire test. Heart rate measurements were averaged across the same 30 second timepoints for future linear modeling, described in detail below.

Data Analysis

Marker trajectories were tracked in Cortex software (Motion Analysis Corp, Rohnert Park, CA, USA) and gap filled and filtered using a zero-lag low-pass Butterworth filter with cutoff frequencies of 8 Hz. Marker data was exported to Visual 3D (C-Motion, Germantown, MD, USA) and a six degree-of-freedom biomechanical model was constructed for the ankle, knee, hip, and torso. Joint angles were calculated using an XYZ Cardan rotation sequence expressing the orientation of the distal segment relative to the proximal, where X corresponded to flexion/extension, Y ab/adduction, and Z axial rotation.

Each gait cycle was defined using the maximum point in the X-direction achieved by the ski tip markers (stride) until the next stride. Joint angles across each gait cycle for the ankle, knee, hip, and torso were exported to MATLAB 2024b (The Mathworks, Natick, MA, USA), where a custom script normalized each to 100% of the gait cycle and computed an ensemble average across fifteen gait cycles for each of the six conditions and stored for future statistical analysis.

In Visual 3D, cycle metrics were computed as averages across each condition as follows: cycle rate, cycle length, cycle time, stance and swing expressed as percent of overall cycle time, and peak step height during the swing phase.

To estimate aerobic metabolic rate (MR_{ac}) and mechanical efficiency (ME) from HR data during the treadmill skinning protocol, linear relationships were calculated between HR and $\dot{V}O_2$ (mean $R^2 = 0.98$), as well as HR and RER (mean $R^2 = 0.91$) for each participant from the walking $\dot{V}O_2$ protocol. Heart rate data across each stage of the skinning protocol was then averaged and the established regression relationships within each participant were used to estimate $\dot{V}O_2$ and RER for each condition during the treadmill skinning.

Calculation of mechanical efficiency, vertical mechanical power, and aerobic metabolic rates during treadmill skiing was carried out according to previous studies by Praz et al¹⁵ and Laaksonen et al²². Vertical mechanical power (VP) was calculated using equation 1:

$$\text{vertical mechanical power [W]} = m \cdot g \cdot \sin(\arctan(\theta)) \cdot v \quad (1)$$

Where m is the mass of the participant including all equipment carried during the test (kg), g is gravity (9.81 m/s^2), θ is the treadmill slope ($^\circ$), and v is the belt speed of treadmill (m/s).

Following estimation of $\dot{V}O_2$ (L/min) and RER (≤ 1.0) from average HR in each condition, aerobic metabolic rate (MR_{ac}) was calculated using equation 2:

$$\text{aerobic metabolic rate [W]} = (4184(\dot{V}O_2 (1.1RER + 3.9)))/60 \quad (2)$$

ME for each trial was then calculated using Margaria's definitions for uphill running²³, as shown in equation 3:

$$\text{mechanical efficiency [\%]} = 100 \cdot \frac{\text{vertical mechanical power}}{\text{net metabolic rate}} \quad (3)$$

Statistical Analysis

Temporal differences in joint angle curves across stance phase between bindings and grades were assessed using statistical parametric mapping (SPM 1D)^{24,25} with a 2x2 repeated measures design in MATLAB. Differences in cycle metrics and variables associated with mechanical

efficiency were assessed using linear mixed effects models²⁶. Binding and grade, as well their interactions were entered in the models as fixed effects with participant entered as a random effect. If a significant fixed effect was found at the $\alpha=0.05$ level, post-hoc pairwise comparisons were performed with a Bonferroni correction while Cohen's d effect sizes were computed to aid in interpretation of results. Effect sizes were interpreted in the ranges of <0.2 small, $0.4 - 0.6$ moderate, > 0.8 large. The above statistical analysis was performed twice, once for comparing the grades and matched speeds, and once for comparing the grades and matched relative intensities. Apart from SPM, all statistical analyses were performed in SPSS Ver. 30 (IBM Corp, Armonk, NY, USA).

Results

Joint angles

At the matched speeds, the SPM analysis showed no significant binding-by-grade interactions, however there were main effects of binding and grade. The main effect of binding was primarily isolated to the ankle and knee joints (Figure 1). There were main effects of binding at the ankle ($F^*=9.676$), knee ($F^*=10.999$), and hip ($F^*=9.382$). The FR binding displayed greater plantarflexion just before (56-63% of gait cycle, $p=.05$) and after (64-80%, $p=.03$) toe-off and greater knee flexion around toe-off (54-68%, $p=.02$). There was also a small cluster with less hip extension at toe-off (62-67%, $p=.05$) with the FR binding. There were main effects of grade across at the ankle ($F^*=9.676$), knee ($F^*=10.999$), hip ($F^*=9.382$), and torso ($F^*=7.865$). At 15% there was greater ankle dorsiflexion from initial contact through midstance (0-31%, $p<.01$), just prior to toe-off (47-62%, $p=.03$), and mid-to-late swing phase (84-100%, $p=.03$). There was also greater knee flexion early in stance (0-24%, $p<.01$) and late in swing phase (82-

100%, $p < .01$), and less knee flexion around toe-off (35-67%, $p < .001$). Finally, the hip and torso showed more hip flexion and less torso flexion across the entire gait cycle (0-100%, both $p < .001$) at the 15% grade.

Statistical parametric mapping results at the matched relative intensity mirrored those from the matched speed, however the size of the clusters was generally smaller (Figure 2). The FR binding results in greater ankle plantarflexion ($F^* = 10.076$) prior to toe-off (57-63%, $p = .04$), greater knee flexion ($F^* = 11.254$) around toe-off (57-67%, $p = .02$), and less hip flexion ($F^* = 9.408$) in mid-stance (36-49%, $p = .04$). Compared to the 8% grade, the 15% grade resulted in greater ankle dorsiflexion ($F^* = 10.076$) from initial contact through midstance (0-30%, $p < .01$), around toe-off (58-70%, $p = .02$), and mid-to-late swing phase (83-100%, $p = .02$). There was also less knee flexion ($F^* = 11.254$) before toe-off and early swing phase (46-78%, $p < .001$), and greater hip flexion through stance phase (36-49%, $p < .01$). Lastly, the torso showed less flexion ($F^* = 9.408$) through midstance (13-39%, $p = .03$) and from late stance through swing (58-83%, $p = .03$) at the 15% grade.

Cycle Metrics

At the matched speed, there were no significant binding-by-grade interactions across any cycle metrics (all $p > .20$). However, cycle rate ($F = 127.8$, $p < .001$), cycle length ($F = 130.4$, $p < .001$), cycle time ($F = 130.5$, $p < .001$), percent stance ($F = 41.8$, $p < .001$), percent swing ($F = 163.8$, $p < .001$), and step height ($F = 45.2$, $p < .001$) all showed significant fixed effects of binding (Table 1). Post-hoc analyses revealed that compared to the P binding, cycle rate ($p < .001$, $d = 0.34$) was lower while cycle length ($p < .001$, $d = 0.36$) and cycle time ($p < .001$, $d = 0.36$) were longer, percent stance ($p < .001$, $d = 0.21$) was shorter, and percent swing ($p < .001$, $d =$

= 0.50) was longer in the FR binding. Step height ($p < .001$, $d = 0.32$) was greater in the FR compared to the P binding.

Additionally at matched speeds, cycle rate ($F = 75.8$, $p < .001$), cycle length ($F = 81.0$, $p < .001$), cycle time ($F = 81.0$, $p < .001$), percent swing ($F = 277.2$, $p < .001$), and step height ($F = 6.0$, $p = .014$) all showed significant fixed effects of grade (Table 1). Percent stance ($F = 0.10$, $p = .75$) did not display a fixed effect of grade. Post-hoc analysis revealed that compared to 8% grade, cycle rate ($p < .001$, $d = 0.26$) was faster, while cycle length ($p < .001$, $d = 0.28$), cycle time ($p < .001$, $d = 0.28$), and percent swing ($p < .001$, $d = 0.66$) were all shorter at the 15% grade. Step height ($p = .014$, $d = 0.12$) was higher at 15% grade.

Similar to the matched speed, at the relative intensity there were no significant binding-by-grade interactions across any cycle metrics (all $p > .20$). Cycle rate ($F = 88.2$, $p < .001$), cycle length ($F = 93.8$, $p < .001$), cycle time ($F = 70.5$, $p < .001$), percent stance ($F = 23.9$, $p < .001$), percent swing ($F = 84.9$, $p < .001$), and step height ($F = 48.6$, $p < .001$) all showed significant fixed effects of binding (Table 2). Post-hoc analyses revealed that compared to the P binding, cycle rate ($p < .001$, $d = 0.36$) was lower while cycle length ($p < .001$, $d = 0.38$) and cycle time ($p < .001$, $d = 0.37$) were longer, percent stance ($p < .001$, $d = 0.22$) was shorter, and percent swing ($p < .001$, $d = 0.22$) was longer in the FR binding. Step height ($p < .001$, $d = 0.35$) was greater in the FR compared to the P binding.

Additionally, cycle rate ($F = 13,155.9$, $p < .001$), cycle length ($F = 10,624.5$, $p < .001$), cycle time ($F = 9,790.1$, $p < .001$), percent stance ($F = 16,071.0$, $p < .001$), percent swing ($F = 1,386.5$, $p < .001$), and step height ($F = 10.3$, $p = .001$) all showed significant fixed effects of grade (Table 2). Post-hoc analysis revealed that cycle rate ($p < .001$, $d = 4.49$) was lower, while

cycle length ($p < .001$, $d = 4.08$) was shorter, cycle time ($p < .001$, $d = 4.28$) was longer, percent stance ($p < .001$, $d = 5.52$) was longer, and percent swing ($p < .001$, $d = 5.52$) was shorter at the 15% grade. Step height ($p = .001$, $d = 0.16$) was lesser at 15% grade.

Table 1. Cycle metrics (mean \pm SD) across 15 gait cycles during the final 30 seconds of each trial of the treadmill skinning protocol at matched speed, compared between bindings and grades.

Variable	Pin (P)		Freeride (FR)		Result
	8%	15%	8%	15%	
Cycle Rate (steps/min)	48.7 \pm 2.79	49.2 \pm 2.80	47.5 \pm 3.28	48.4 \pm 2.71	A, B
Cycle Length (m)	1.38 \pm 0.08	1.37 \pm 0.08	1.42 \pm 0.10	1.39 \pm 0.07	A, B
Cycle Time (s)	1.24 \pm 0.07	1.22 \pm 0.07	1.27 \pm 0.08	1.24 \pm 0.07	A, B
Percent Stance (%)	61.2 \pm 4.65	62.3 \pm 4.46	60.8 \pm 5.22	61.7 \pm 4.46	A
Percent Swing (%)	38.8 \pm 2.98	37.7 \pm 2.93	39.2 \pm 3.74	38.3 \pm 2.95	A, B
Step Height (cm)	2.39 \pm 1.05	2.59 \pm 1.41	2.83 \pm 1.10	2.90 \pm 1.20	A

Note. A and B indicate significant effects of binding and grade, respectively, at the $p < .05$ level.

Table 2. Cycle metrics across (mean \pm SD) 15 gait cycles during the final 30 seconds of each trial of the treadmill skinning protocol at matched relative intensity, compared between bindings and grades.

Variable	Pin (P)		Freeride (FR)		Result
	8%	15%	8%	15%	
Cycle Rate (steps/min)	48.7 \pm 2.79	35.9 \pm 2.50	47.5 \pm 3.28	35.0 \pm 2.59	A, B
Cycle Length (m)	1.38 \pm 0.08	1.05 \pm 0.08	1.42 \pm 0.10	1.08 \pm 0.08	A, B
Cycle Time (s)	1.24 \pm 0.07	1.68 \pm 0.12	1.27 \pm 0.08	1.72 \pm 0.13	A, B
Percent Stance (%)	61.2 \pm 4.65	65.9 \pm 7.03	60.8 \pm 5.22	64.9 \pm 7.80	A, B
Percent Swing (%)	38.8 \pm 2.98	34.1 \pm 6.85	39.2 \pm 3.74	35.1 \pm 7.27	A, B
Step Height (cm)	2.39 \pm 1.05	2.20 \pm 1.05	2.83 \pm 1.10	2.62 \pm 1.59	A, B

Note. A and B indicate significant effects of binding and grade, respectively, at the $p < .05$ level.

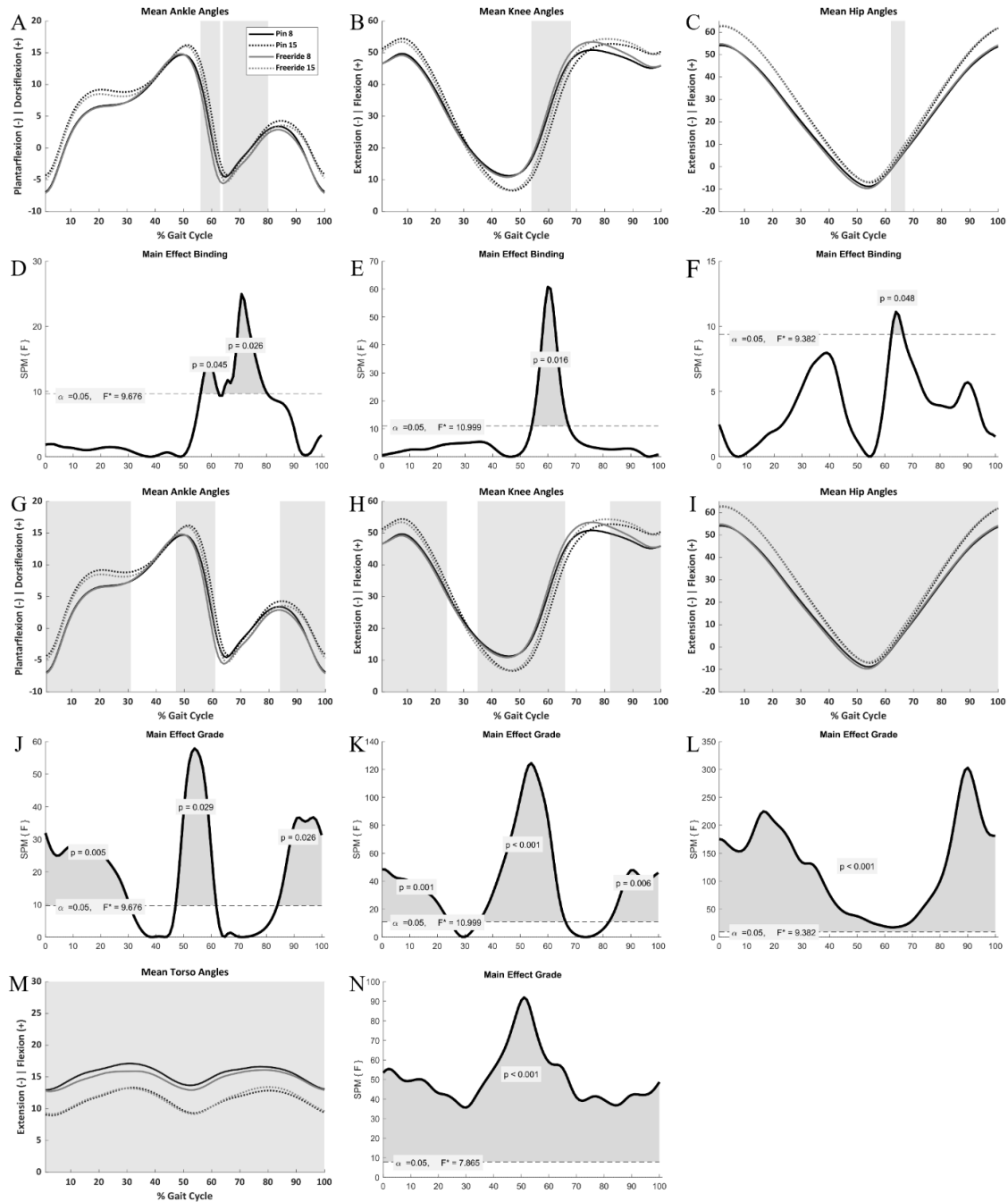


Figure 1. Average joint angles, normalized to 100% of gait cycle, and corresponding SPM{F} plots for matched speed. Main effects of binding on ankle (A), knee (B), and hip (C) with corresponding SPM{F} plots (D, E, F respectively) displayed below. Main effect of grade on ankle (G), knee (H), and hip (I) and SPM{F} plots (J, K, L respectively) are shown in rows two and three. There was no significant effect of binding on the torso at matched speed, however main effect of grade on torso (M) and SPM{F} plot (N) are displayed in the fifth row.

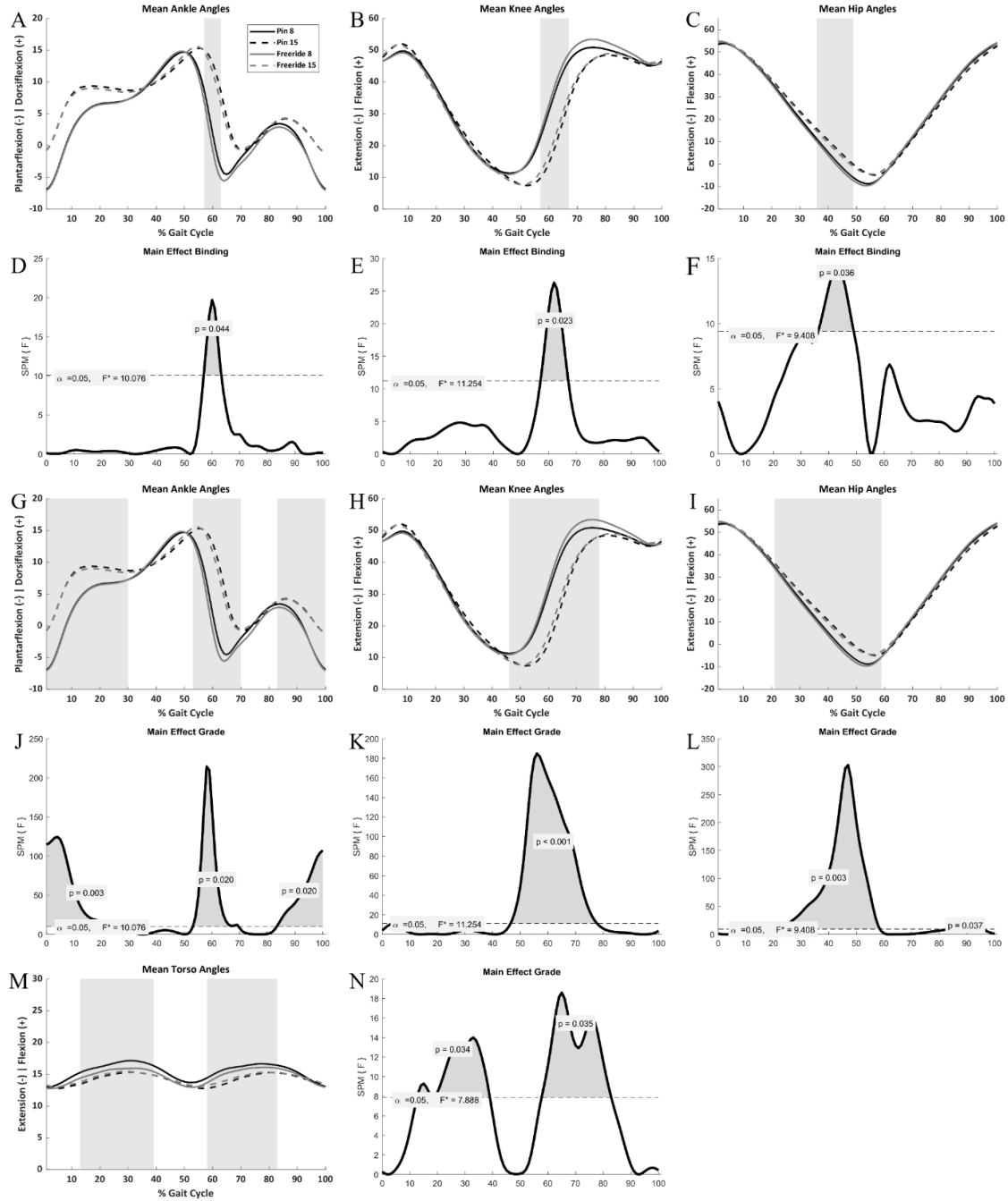


Figure 2. Average joint angles, normalized to 100% of gait cycle, and corresponding SPM{F} plots for relative intensity. Main effects of binding on ankle (A), knee (B), and hip (C) with corresponding SPM{F} plots (D, E, F respectively) displayed below. Main effect of grade on ankle (G), knee (H), and hip (I) and SPM{F} plots (J, K, L respectively) are shown in rows two and three. There was no significant effect of binding on the torso at relative intensity, however main effect of grade on torso (M) and SPM{F} plot (N) are displayed in the fifth row.

Vertical Power, Metabolic Rate, and Mechanical Efficiency

There were no significant binding-by-grade interactions for VP, MR_{ac}, or ME at matched speed (all $p > .85$). Additionally, there was no fixed effect of binding on VP ($F = 0.185, p = .69$), MR_{ac} ($F = 0.257, p = .61$), or ME ($F = 0.057, p = .81$). There was a significant fixed effect of grade on VP ($F = 412.2, p < .001$), MR_{ac} ($F = 17.21, p < .001$), and ME ($F = 107.9, p < .001$). Post-hoc analyses revealed that VP ($p < .001, d = 4.3$), MR_{ac} ($p < .001, d = 0.7$), and ME ($p < .001, d = 1.83$) were higher at 15% (Table 3).

Similarly, there were no significant binding-by-grade interactions for VP, MR_{ac}, or ME at the relative intensity (all $p > .85$). Additionally, there was no fixed effect of binding on VP ($F = 0.210, p = .65$), MR_{ac} ($F = 0.350, p = .56$), or ME ($F = 0.057, p = .81$). There was no significant fixed effect of grade on VP ($F = 2.228, p = .14$). However, there was a significant fixed effect of grade on MR_{ac} ($F = 16.42, p < .001$), and ME ($F = 29.33, p < .001$). Post-hoc analyses revealed that MR_{ac} ($p < .001, d = 0.7$) was lower, while ME ($p < .001, d = 1.15$) was higher at 15% (Table 4).

Table 3. Vertical power, metabolic rate, and mechanical efficiency (mean \pm SD) between bindings and grades, averaged across the last 30 seconds of each 3-minute stage of the treadmill skinning protocol at matched speed.

Variable	Pin (P)		Freeride (FR)		Result
	8%	15%	8%	15%	
Vertical Power (W)	69.2 \pm 9.3	128.9 \pm 17.3	70.1 \pm 9.3	130.5 \pm 17.4	B
Metabolic Rate (W)	839.3 \pm 248.2	1050 \pm 314.7	872.8 \pm 262.7	1066 \pm 321.0	B
Efficiency (%)	8.72 \pm 2.0	12.9 \pm 2.6	8.6 \pm 2.1	12.9 \pm 2.6	B

Note. A and B indicate significant effects of binding and grade, respectively, at the $p < .05$ level.

Table 4. Vertical power, metabolic rate, and mechanical efficiency (mean \pm SD) between bindings and grades, averaged across the last 30 seconds of each 3-minute stage of the treadmill skinning protocol at matched relative intensity.

Variable	Pin (P)		Freeride (FR)		Result
	8%	15%	8%	15%	
Vertical Power (W)	69.2 \pm 9.3	72.2 \pm 9.7	70.1 \pm 9.3	73.1 \pm 9.7	
Metabolic Rate (W)	839.3 \pm 248.2	667.8 \pm 230.3	872.8 \pm 262.7	686.5 \pm 221.5	B
Efficiency (%)	8.7 \pm 2.0	11.6 \pm 2.6	8.6 \pm 2.1	11.5 \pm 3.3	B

Note. A and B indicate significant effects of binding and grade, respectively, at the $p < .05$ level.

Discussion

The purpose of this study was to compare lower body kinematics and energetic demands during uphill skinning with pin and free ride bindings at two slope gradients in a recreational skier population. In partial support of our first hypothesis, ankle, knee, and hip kinematics showed just a few small differences between bindings, with differences being no more than 2 degrees of motion. The differences did not depend on the grade. Our second hypothesis was also partially supported, as there were slower cycle rates and longer cycle lengths in the FR binding across both grades, however step height was greater in the FR binding contrary to the hypothesis. In partial support of our third hypothesis, there were no differences in mechanical efficiency between bindings, however this was because there were no difference in vertical power output, metabolic rate, not because these values increased in the FR binding.

Changes in kinematics

While statistical analysis revealed small clusters where binding type influenced sagittal plane joint angles, the magnitude of these differences were within the range of minimal

detectable change of marker-based motion capture systems. Previous research on the reliability and minimal detectable change values for gait kinematics in similar motion capture systems have found that in healthy adults only changes in kinematics of greater than 5° can be reliably identified²⁷. The changes in joint curves presented in the current study between bindings were generally no more than $1-2^\circ$ of joint motion and thus may be within the measurement error of the motion capture system.

The effect of binding on joint kinematics were primarily located around toe-off in the ankle, knee, and hip. One potential explanation for these changes may be the increased mass of the FR binding. Given that both bindings attach to the toe piece of the boot in the same location, the moment arm between the toe pivot point and ankle pivot points are identical in each binding. However, the increased mass of the FR binding results in a greater weight force, which acts where the bindings connect to the toe piece of the boot, thus a larger external plantarflexion moment at the ankle as the ski/binding system is lifted off the treadmill during toe-off and swing phase. This may explain the increase in ankle plantarflexion around toe-off and the beginning of swing phase in the FR binding in the absence of increased torque from the ankle dorsiflexor muscles. With increased ankle plantarflexion, knee flexion would also be increased to create sufficient ground clearance between the ski and treadmill belt during swing phase. This is supported by the increase in SH observed in the FR binding. However, while statistically significant, the functional implications of these differences are unclear as the magnitude of actual differences between bindings for ankle plantarflexion and knee flexion ($1-2^\circ$) and SH ($\sim 0.2\text{cm}$), and the corresponding effect sizes were very small.

The effect of grade on joint angles had a similar result to a previous literature on treadmill walking with increasing grade^{17,18}. Both studies found that as grade increased from 8% to 15%, participants exhibited less hip extension through stance phase, greater knee flexion at heel strike, greater ankle dorsiflexion at heel strike, and less ankle plantarflexion at toe-off. Our results show a similar pattern occurs in skimo, as skinning gait may be very closely related to walking gait. Future studies could build on this finding through a comparison of how gait changes from walking to treadmill skinning, as building the ability to generalize results found in walking gait studies to skimo could help increase the body of knowledge around skimo biomechanics. This should be examined with the caveat that skinning gait may differ between a rubber treadmill belt and actual on-snow activity, as the ability to slide the ski surface across the ground surface is affected.

The increased mass of the FR binding may explain the observed effects of binding on cycle metrics, specifically on cycle rate and length. The greater mass of the FR binding may result in greater momentum of the ski/binding system during the swing phase, thus causing the foot to swing further in front of the body before foot contact, resulting in lower cycle rates and longer cycle lengths. However, given the relatively small differences in cycle metrics between bindings, combined with the small effect sizes for the effect of binding, and the fact that no differences in power, metabolic rate, or efficiency were found, these changes are likely not of concern to a recreational skier.

The effects of grade on cycle metrics are similar to what has previously been reported both on a ski treadmill and on-snow^{15,16}. In the laboratory portion of the Praz et al study¹⁶, the researchers examined spatiotemporal variables of cycle rate, cycle length, and percent stance

time change across changes in treadmill grades and speeds in elite skimo athletes. As grade increased (10%, 17%, 24%) and speed was matched, a tendency towards faster cycle rate ($p = .06$) and significantly shorter cycle length and greater stance time was observed. Our results are very similar, with faster cycle rate and shorter cycle length as grade increases at the matched speed. While those authors did not directly control for matched relative intensity as grade increases, they did examine slower speeds at each increasing grade, keeping the percentage of HR_{max} similar between conditions. Therefore, the results may be comparable to our results at the relative intensity. As grade increased and exercise intensity was matched, they found cycle rate was lower, cycle length was shorter, and percent stance was longer. This aligns with our results on the effect of grade at matched relative intensity, which saw cycle rate was lower, cycle length was shorter, and percent stance was longer. The results of the on-snow portion of the research by Praz et al¹⁵ had matching findings for the effect of grade on cycle metrics at matched relative intensity.

Vertical power, metabolic rate, and efficiency

We saw no effect of binding on VP, MR_{ac} , or ME in recreational skiers, which aligns with previous findings from Tosi et al (2009). While they artificially added weight to the ankle of skiers, their results showed that for a 1 kg total increase in equipment mass, they saw a 2% increase in energetic cost, which they postulated was likely negligible for a recreational skier, but not a competitive skimo athlete⁶. Other studies have found larger changes in energetic cost with increasing equipment weight where there was roughly a 2% increase for every 0.2 kg added⁵, and 6.5% and 18% increases in energetic costs for equipment weight changes of 1.8 and 4.3 kg respectively⁷. However, it should be noted that in the study by Bortolan et al (2024)⁵ the

population of interest was a competitive skimo racers, studied at higher grades and speeds which may greatly affect the relationship between weight and energy cost. Skinner et al (2019)⁷ compared an extremely lightweight skimo racing setup (binding and ski) and a much heavier frame style touring binding which has a completely different mechanism to attach the boot and binding for uphill travel, where the entire binding moves with the boot on every step. Thus, the findings of these studies are difficult to compare to the present study, where we compared more modern skimo setups that are typically used by recreational skiers, a lightweight P binding and a hybrid FR binding mounted to freeride skis. In the present study, the total weight increase from the P setup to the FR setup was 0.96 kg, and we saw no statistically significant changes in VP, MR_{ae}, or ME. This finding is supported by the negligible effect of binding on joint kinematics and cycle metrics shown in this study. For a recreational skier, there is likely no difference between the P and FR binding for uphill travel under the testing conditions.

Limitations

We only compared two grades, which while different, represent relatively moderate grades compared to those encountered during skimo touring. Changes in kinematics across steeper grades should also be considered to get a better understanding of how these bindings may change across steeper grades that may be encountered during actual skimo tours. However, changes to the study design would need to be taken into account, as without skins on the bottom of the skis, skiers began to slip on the treadmill belt around 20% in pilot testing.

The use of the treadmill inherently limits the external validity of our results. An on-snow comparison of these bindings must be performed in future studies to determine how or if differences in the laboratory may transfer to real ski touring scenarios. During this testing,

analysis of the downhill performance of these bindings should be taken into consideration, as a large part of recreational skier binding choice is made on the downhill safety and performance of the binding.

Conclusion

In this study we conducted a laboratory-based comparison of biomechanics and energetic demands between two common binding designs for ski mountaineering across two grades and speeds in recreational ski mountaineers. Our results indicate that there are negligible differences in sagittal plane joint kinematics and cycle metrics between the P and FR binding for uphill skiing. Additionally, we found no differences in the vertical power demand, metabolic rate, or mechanical efficiency between the two bindings, further supporting that changes in biomechanics were too small to influence the energetic cost of uphill travel. However, further research examining the differences between these bindings across steeper grades, on snow, and downhill performance must be considered to get a clearer understanding of differences between these binding styles.

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CHAPTER FOUR

CONCLUSIONS AND FUTURE DIRECTION

Ski mountaineering, or skimo, is one of the fastest growing winter activities in the United States, with the total number of participants expected to triple to 2.2 million people from 2019 to 2023¹. Skimo is popular for both recreational and competitive populations², however the equipment used by these populations looks very different. A key reason for these differences is that recreational skimo participants tend to prioritize the downhill portion of the activity³, and tend to choose equipment designed for better downhill performance and safety. Alternatively, competitive skimo racing is an extreme endurance activity and therefore athletes prioritize lightweight equipment. Any excess weight carried by the athlete is shown to be detrimental to performance⁴⁻⁷.

While previous studies on competitive skimo athletes have shown a strong correlation between equipment weight and metabolic cost⁴⁻⁷, how weight influences skinning kinematics and energy cost in recreational skiers remains unknown. This is an impactful question, as participants generally choose between lightweight pin or heavier freeride bindings. Therefore, the purpose of this study was to compare lower body kinematics and energetic demands during uphill skinning while using pin and freeride bindings at two slope gradients within a recreational skier population.

Participants completed three-minute bouts using matching skis, mounted with either the Backland Tour pin or the Shift 13MN freeride bindings. With each binding type skinning trials were performed at 8% and 1.1 m/s and 15% at both 0.63 m/s and 1.1 m/s. Two speeds were used at the higher grades to have conditions with matched speeds and matched relative intensities

across the grades, leaving any differences in mechanical efficiency as being solely due to changes in metabolic rate. Lower body kinematics, cycle metrics, vertical power, metabolic rate, and mechanical efficiency were calculated and compared across bindings and grades.

The results of this study indicate that there are negligible differences in sagittal plane joint kinematics and cycle metrics between the pin and freeride binding for uphill skinning in recreational skiers. Additionally, we found no differences in the vertical power demand, metabolic rate, or mechanical efficiency between the two bindings, further supporting that changes in biomechanics were too small to influence the energetic cost of uphill travel.

The current study has limitations that should be considered while interpreting these results. We only compared two grades, which while different, represent relatively moderate grades compared to those encountered during actual skimo touring. Changes in kinematics across steeper grades should also be considered to get a better understanding of how these bindings may change across steeper grades that may be encountered outdoors. In addition, skins were not used in this study to prevent damage to the skins and treadmill. This may cause changes the kinematics and efficiency of skinning, as the skins would theoretically reduce friction when sliding the ski forward, allowing easier gliding/skinning motion.

Testing these effects on a treadmill inherently limits the external validity of our results. On-snow comparison of these bindings must be performed in future studies to determine if differences in the laboratory transfer to real ski touring scenarios. During this testing, analysis of the downhill performance of these bindings should be taken into consideration, as a large part of recreational skier binding choice is made upon the downhill safety and performance of the binding.

Building on these limitations, there are several future questions that can be addressed to cultivate a larger depth of knowledge in the field of ski mountaineering. A follow-up study examining how the research question addressed in the current study should be performed in the field, addressing laboratory to on-snow validity of results. During this research, differences between these bindings should be assessed over longer durations and a wider range of slope angles. The downhill performance of these bindings should be considered as well, such as skier kinematics and kinetics. Qualitative measures could be collected on participant preference, enjoyment, and binding security to get a clearer picture of what recreational participants prefer during downhill skimo.

A current gap in the literature is how to define skimo skinning gait. A large body of literature exists for activities such as walking and running, defining common mechanics that can be used to standardize the language used to describe these activities. No such studies are currently published for skimo. Future work should define the mechanics of skimo gait both in a laboratory setting and in the field to provide a framework for future biomechanical analysis of ski mountaineering.

In summary, in this thesis we conducted a laboratory-based comparison of biomechanics and energetic demands between two common binding designs for ski mountaineering across two grades and speeds. Results indicate that there are negligible differences in kinematics, and no differences in energetic cost between the pin and freeride bindings for uphill skinning in recreational skiers. However, further research examining the differences between these bindings across steeper grades, on snow, and downhill performance must be considered to get a clearer understanding of differences between these binding styles.

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