

THE INFLUENCE OF SPLITBOARD BINDINGS AND TOURING-SPECIFIC
BOOTS ON MUSCLE ACTIVITY, STRIDE LENGTH, AND JOINT KINEMATICS
DURING SPLITBOARD TOURING

by

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TABLE OF CONTENTS

1. INTRODUCTION	1
Purpose Statement.....	4
Rationale	5
Limitations	5
Assumptions.....	5
Hypotheses	6
2. REVIEW OF RELATED LITERATURE	8
Electromyography	10
Stride Length.....	13
Kinematic Analysis.....	14
Conclusion	16
3. THE INFLUENCE OF SPLITBOARD BINDINGS AND TOURING- SPECIFIC BOOTS ON MUSCLE ACTIVITY, STRIDE LENGTH, AND JOINT KINEMATICS, DURING SPLITBOARD TOURING	17
Abstract.....	17
Introduction.....	18
Methodology	21
Informed Consent.....	21
Subjects	21
Experimental Design.....	22
Protocols: First Visit	24
VO ₂ max testing.....	24
Protocols: Second Visit.....	25
Initial Setup.....	25
Heart Rate	26
Electromyography Setup and Collection	26
Kinematic Setup and Collection	27
Procedures.....	28
Data Analysis	28
Electromyography Analysis.....	28
Stride Length.....	29
Kinematic Analysis.....	32
Statistical Analysis.....	33
Results.....	34
Electromyography.....	34
Stride Length.....	38
Kinematic Analysis.....	42

TABLE OF CONTENTS CONTINUED

Discussion	44
Stride Length.....	45
Kinematic Analysis.....	47
Electromyography.....	49
Limitations	52
Future Research	54
Conclusion	56
REFERENCES CITED.....	58
APPENDICES	64
APPENDIX A: Informed Consent Form	65
APPENDIX B: VO ₂ max Data Collection Sheet.....	69
APPENDIX C: Calculation of HR60.....	71
APPENDIX D: Testing Data Collection Sheet.....	73

LIST OF TABLES

Table	Page
2.1. Working definitions for phases of a splitboard gait cycle	9
3.1. Subject Anthropometric Data	22
3.2. Test conditions	23
3.3. The Bruce protocol for VO ₂ max testing	25
3.4. Legend for all tables and graphs	35
3.5. Descriptive statistics for EMG (reported as average RMS) results	35
3.6. Stride length descriptive statistics.....	39
3.7. Ankle and knee ROM descriptive statistics	42

LIST OF FIGURES

Figure	Page
1.1. Spark R&D bindings with the Rip and Flip highback.....	3
1.2. Burton Driver X and Tourist snowboard boots.....	4
3.1. Phases of walking gait	30
3.2. Accelerometer and EMG data from the TA EMG sensor.....	31
3.3. The phases of the splitboard gait cycle compared to ankle and knee joint angles during uphill touring	33
3.4. Comparison of EMG (reported as average RMS) results by test condition.....	36
3.5. Comparison of EMG (reported as average RMS) results between boot models.....	36
3.6. Comparison of EMG (reported as average RMS) results between binding settings.....	37
3.7. Individual analysis of EMG results for MG	37
3.8. Individual analysis of EMG results for TA.....	38
3.9. Comparison of mean stride length in the four test conditions	39
3.10. Comparison of mean stride length between boot models	40
3.11. Comparison of mean stride length between binding settings	40
3.12. Individual analysis of stride length results.....	41
3.13. Correlation analysis between years of splitboarding experience and stride length coefficient of variation	41
3.14. Comparison of mean ankle range of motion by test condition	43
3.15. Comparison of mean knee range of motion by test condition	43
3.16. Comparison of mean range of motion between boot models	44

LIST OF FIGURES CONTINUED

Figure	Page
3.17. Comparison of mean range of motion between binding settings	44

ABSTRACT

Splitboarding is a form of alpine recreation that involves using a snowboard that splits into two skis to tour in backcountry terrain. At the summit, the skis are attached together and used as a normal snowboard to ride downhill. As splitboarding has grown in popularity, manufacturers have developed splitboard-specific equipment, such as bindings and boots. This crossover study investigated the effects of highback lean settings on Spark R&D splitboard bindings and two Burton Snowboards boot models while touring uphill. Subjects toured on a treadmill at a 10% incline in four test conditions: the Driver X boot with positive lean, the Driver X boot with negative lean, the Tourist boot with positive lean, and the Tourist boot with negative lean. Lower limb muscle activity was recorded as average root-mean-square (RMS) for gluteus medius (GM), biceps femoris (BF), rectus femoris (RF), medial gastrocnemius (MG), and tibialis anterior (TA). Kinematics variables of stride length, and ankle and knee range of motion (ROM) were also measured. The effects of the boots and bindings were determined using a two-way repeated measures analysis of variance ($\alpha < 0.05$). The main effect of binding on average RMS was not significant for all muscles except MG ($F = 8.821, p = 0.018, f = 1.05$), with the negative lean having higher average RMS than the positive lean. The main effect of boot on stride length was significant ($F = 15.791, p = 0.003, f = 1.33$), with the Tourist resulting in a 3.56 cm longer stride length than the Driver X. The main effect of binding on stride length was also significant ($F = 9.875, p = 0.012, f = 1.05$), with negative lean resulting in a 2.21 cm longer stride length than the positive lean. The main effect of boot model on ankle ROM was significant ($F = 36.325, p = 0.000, f = 2.00$), with the Tourist having a larger ROM than the Driver X. There were no significant effects or interactions for knee ROM. The results of this study demonstrate that boot model and binding settings can affect biomechanical and physiological variables while splitboard touring.

CHAPTER ONE

Introduction

According to Snowsports Industries America (SIA), the number of winter sports enthusiasts exploring backcountry (not lift-accessed) terrain has increased steadily since 2008 (SIA, 2015b). Although participation rates are weather-dependent, in 2015 1.2 million snowboarders recreated in backcountry terrain (SIA, 2015b). “Touring” is the act of ascending, or travelling uphill, in backcountry terrain. In 2015, sales of alpine touring equipment increased 8%, or by \$19 Million (SIA, 2015b). The demographic distribution of snowboarders is 61.6% male, and 62.6% between the ages of 18 and 44 (SIA, 2015c).

Splitboarding is a type of snowboarding used to access backcountry terrain (Van Tilburg, 2000). A splitboard is a snowboard that can be divided longitudinally into two skis. When separated, the skis are used to tour uphill using a motion similar to backcountry skiing. During uphill touring, the heel of the binding is free, or unattached to the ski. The toe of the binding is attached to the ski using a pin or hinge system. At the summit, the bindings are removed from the skis and re-attached horizontally to the board in a manner that clips the skis together, forming a snowboard. During descent, the splitboard functions as a normal snowboard. Splitboard sales have steadily increased from 2010 to 2014, which resulted in \$1.93 million in revenue in the 2014-15 season (SIA, 2015a; SIA, 2015b). At present, splitboarders are a small subset of snowboarders due to limitations imposed by cost and challenges of accessibility.

The biomechanical motion of touring uphill appears to be very similar to that of backcountry skiing and classic cross-country skiing. All methods of travel feature an

unlocked heel, a locked toe, and use a combined stepping, lunging, and gliding motion to move uphill across the snow. A splitboard ski is generally shorter and wider than an alpine or cross-country ski. Snowboard boots are typically made of stiff fabric, while ski boots are made of hard plastic.

One of the primary goals of splitboarding is to access backcountry terrain that is unique, high-quality, and less accessible to the public. In an effort to improve the quality of improve backcountry touring, snowboard companies are developing products designed to make touring easier, more comfortable, and more efficient. The purpose of these products is to improve the splitboard experience so that the users are able to access more terrain while expending less energy. Historically, splitboarders have been limited to using binding systems that are bulky, heavy, and prone to malfunction. Spark R&D splitboard bindings are specifically designed to help splitboarders access backcountry terrain (Spark R&D, 2016).

Since 2015, Spark R&D bindings feature a “Rip and Flip Highback” (Figure 1.1). The highback is the vertical piece of the binding that provides support behind the calf and posterior boot. The majority of snowboard bindings have a highback that is restricted to various amounts of positive (forward) lean, and that are not adjustable during use. On snowboard bindings, positive lean is designed to push user’s ankle into slight dorsiflexion and provide support behind the calf. Spark R&D’s bindings feature a highback that can be adjusted to provide support from +22° of positive lean to -13° of negative lean (Spark R&D, 2016). It is hypothesized that the negative lean setting allows for a greater range of motion at the hip, knee, and ankle, which may alter biomechanical and physiological function while touring. For example, the increased range of motion would allow the user

to increase their stride length. In specific types of terrain, a longer stride may influence muscle activity, joint kinematics, and/or stride length. For example, while traversing across flat or low-incline terrain, a longer stride will allow for a splitboarder to decrease stride frequency while maintaining the same speed.



Figure 1.1 – A Spark R&D binding showing the range of motion of the Rip and Flip Highback. Source: Tactics Boardshop.

One hypothesized problem with negative lean is that many traditional snowboard boots do not allow for rearward flexion, which inhibits use of the full range of motion in Spark R&D bindings. To help resolve this issue, Spark R&D and Burton Snowboards have collaboratively designed the Burton Tourist – a snowboard boot specifically for splitboard touring that can take advantage of negative lean. The Burton Tourist boot has a similar design to the Driver X, which is one of Burton’s stiffest and most popular backcountry boots (Figure 1.2). The two boot models feature the same outsole, but the Tourist has enhanced articulations at the ankle and calf that are hypothesized to allow for increased range of motion within the binding. However, if Tourist was to be used in a binding with positive lean only, it would be prevented from flexing rearwards. Use of the Tourist boot with Spark R&D bindings pairs two unique products that are designed to

help make splitboard touring more comfortable and efficient. The purpose of this study is to explore the relationships between the boot models, binding settings, physiology and biomechanics of the body while touring uphill. The effects and interactions of the Tourist boot and Rip and Flip highback have never formally been studied on human subjects.



Figure 1.2 – At left, the traditional design Burton Driver X snowboard boot; at right, the splitboard-specific Burton Tourist snowboard boot, with points of enhanced articulation. Source: Burton Snowboards.

Purpose Statement

The purpose of this study is to understand the effects and interactions of positive and negative lean on Spark R&D splitboard bindings and Driver X and Tourist model Burton snowboard boots on muscle activity and kinematics during uphill treadmill touring.

Rationale

The purpose of splitboarding is to effectively climb a mountain in order to ride down. New technology in splitboarding attempts to make this ascent easier and more efficient for the user. The rationale of this study is to understand the effects of this equipment on physiological and biomechanical parameters while touring uphill, and to provide data that can be used in manufacturing research and development to improve splitboarding products.

Limitations

A limited number of boots were provided for the study, so subjects wore the size closest to their normal boot size. One of the most significant limitations to the study is the difference in the touring surface between the treadmill track and snow. On snow, splitboarders are able to glide with each step. On the treadmill, a normal touring motion is possible, but the board cannot glide against the surface.

Assumptions

It was assumed that all subjects followed instructions provided prior to the two days of testing. In addition, all instrumentation utilized for measuring physiological and biomechanical variables will be assumed to be reliable and valid. The Spark R&D Arc bindings and the Burton Driver X and Tourist snowboard boots used for the study are assumed to be consistent in function between sizes, and to retain workability throughout testing.

Hypotheses

NULL HYPOTHESIS (1): There will be no difference between the positive and negative lean settings on Spark R&D Arc Bindings while touring at a 10% grade.

H_{01} : μ_{POS} (EMG, stride length, ankle joint range of motion, knee joint range of motion) = μ_{NEG} (EMG, stride length, ankle joint range of motion, knee joint range of motion)

NULL HYPOTHESIS (2): There will be no difference between the Driver X and Tourist snowboard boots while touring at a 10% grade.

H_{02} : μ_{DRV} (EMG, stride length, ankle joint range of motion, knee joint range of motion) = μ_{TOUR} (EMG, stride length, ankle joint range of motion, knee joint range of motion)

ALTERNATIVE HYPOTHESIS (1): There will be an increase in stride length, muscle activity, ankle joint range of motion, and knee joint range of motion while using the negative lean settings on Spark R&D Arc Bindings while touring at a 10% grade

H_{A1} : μ_{POS} (EMG, stride length, ankle joint range of motion, knee joint range of motion) < μ_{NEG} (EMG, stride length, ankle joint range of motion, knee joint range of motion)

ALTERNATIVE HYPOTHESIS (2): There will be an increase in stride length, muscle activity, ankle joint range of motion, and knee joint range of motion while using Burton Tourist snowboard boot while touring at a 10% grade

H_{A2} : μ_{DRV} (EMG, stride length, ankle joint range of motion, knee joint range of motion) < μ_{TOUR} (EMG, stride length, ankle joint range of motion, knee joint range of motion)

CHAPTER TWO

Review of Related Literature

Very little physiological or biomechanical research exists in the field of splitboarding or snowboarding. The majority of previous research has focused on snowboarding injuries (Ehrnthaller, Gebhard, & Kusche, 2015; Ehrnthaller, Kusche, & Gebhard, 2014; Haverkamp, Hoornenborg, Maas & Kerkhoffs, 2014; Steenstrup, Bere, & Bahr, 2014; Major, Steenstrup, Bere, Bahr, & Nordsletten, 2013), asymmetries in leg strength (Vernillo, Pisoni, & Thiebat, 2016) joint loading while riding downhill (Klous, Müller, & Schwameder, 2014), and competitive performance (Platzer, Raschner, Patterson, & Lember, 2009).

Although a splitboard touring motion is similar to walking and a classic cross-country ski stride (as described in the introduction), there are several important distinctions. Table 2.1 provides working definitions of the phases of the splitboard gait cycle that will be used throughout this study. The splitboard touring movement utilizes an elongated walking motion, and but does not lift the suspended limb high in the air during the swing phase. Instead, during swing phase, the ski slides along the ground by the toe of the boot as they transition from push-off to foot strike. At foot strike, the user typically glides on the snow surface on the plant foot ski. The primary motions of the lower limbs that occur at various stages of the stride are hip flexion, hip extension, knee flexion, and knee extension. The amount of ankle dorsiflexion and plantar flexion that may occur are dependent on the user's stride and the stiffness/restrictiveness of the boot and binding complex. Other factors to consider include the heavier weight, larger width, and shorter

length of a splitboard ski. The biomechanical similarity between a classic cross-country ski and splitboard motion suggests that similar muscle activation patterns should exist between the two sports.

Gait cycle term	Definition
Foot strike	Comparable to heel strike in a walking gait; the reference foot is in full contact with the ground following swing phase.
Glide	After initial contact is made with the ground, the foot and ski glide along the snow. The contralateral limb extends at the hip and knee, while the reference limb flexes at the hip and knee. The length of the glide is dependent on the slope incline, equipment, snow quality, and user preference.
Mid-stance	Following glide, the reference foot remains in full contact with the ground and supports body weight as the contralateral foot is in swing phase.
Terminal stance	At the end of mid-stance, the reference limb prepares for push off through slight flexion at the hip and knee, and dorsiflexion at the ankle.
Push off	Swing phase is initiated by the user extending the hip and knee, while plantar flexing at the ankle.
Swing phase	The reference foot is not in direct contact with the ground. The heel is raised, and the user slides the ski forward using the hinge of the binding that connect the toe to the ski. The ski remains in contact with the ground.

Table 2.1 – Working definitions for phases of a splitboard gait cycle

In 2010, Tosi Leonardi, Zerbini, Rosponi, & Schena reported that backcountry skiers self-select a speed that minimizes their metabolic cost. The implication of these findings is that if a skier or splitboarder is not restricted in their climbing motion by their equipment, they should be able to self-select a pattern of movement (including stride frequency and length) that is the most physiologically efficient for them. In 2016, Praz

Fasel, Vuistiner, Aminian, & Kayser reported that during uphill ski mountaineering at an 11% grade, energy expenditure and mechanical efficiency did not vary with speed. Further research may reveal how the Spark R&D Rip and Flip highback can impact physiological and biomechanical variables to improve efficiency and comfort while touring.

Electromyography

Electromyography (EMG) is the study of electrical activity within muscle tissue. Surface EMG involves placing sensors on top of the skin to measure electrical activity as a muscle contracts (De Luca, 1997). Electromyography is a commonly used tool in physiological and biomechanical research to improve understanding of muscle activity and activation, relationships to force production, and as an indicator of fatigue (De Luca, 1997). Electromyography has been used for decades in both laboratory and field settings, but is susceptible to influence by intrinsic and extrinsic factors, such as muscle pennation and the location of the sensor on the muscle, that can affect the recording and analysis of the EMG signal. Surface EMG has proved to be a valuable tool during analysis of walking, running, snowboarding, and skiing.

Research application of EMG includes studies on walking and running in both laboratory and field settings. During a comprehensive analysis of walking and running, Wall-Scheffler, Chumanov, Steudel-Numbers, & Heiderscheit (2010) found that lower-limb muscle activation patterns increased with increased intensity (speed, incline, and stride length). In 2000, Swanson & Caldwell investigated the effects of incline and level treadmill running on lower body EMG. During incline running, Swanson & Caldwell

found an increase in the average EMG amplitude in the gastrocnemius, soleus, vastus lateralis, rectus femoris, and gluteus maximus, and a decrease in the biceps femoris activity. Alexander & Schwameder (2016) used EMG analysis of the biceps femoris, rectus femoris, vastus lateralis, tibialis anterior, and gastrocnemius lateralis to correlate muscle activity with various inclinations (0° , $\pm 6^\circ$, $\pm 12^\circ$, and $\pm 18^\circ$) during walking. The researchers found an increase in muscle activity at inclines compared to level walking for all muscles measured.

Electromyography research has also been applied on-hill to skiers and snowboarders. Recent research by Falda-Buscaiot and Hintzy (2015) used EMG to observe differences in muscle activation patterns in skiers and snowboarders. The researchers placed EMG sensors on the tibialis anterior, gastrocnemius medialis, vastus lateralis, rectus femoris, semitendinosus, and gluteus maximus muscles of both lower limbs. Falda- Buscaiot and Hintzy found that, alpine skiing and snowboarding exerted similar patterns of muscular activity during on-hill turns, except that snowboarders had higher muscle activation in the calf muscles. In 2013, Jinho et al. also studied muscle activation patterns using EMG in a case study of two professional downhill snowboarders. The muscles monitored were vastus medialis, vastus lateralis, and lateral gastrocnemius. The researchers found asymmetrical recruitment patterns between the front and rear legs during alpine and boardercross training.

Root Mean Square amplitude (RMS) is a method to analyze the amplitude of an EMG signal. Root mean square is a moving average, and is calculated by taking the square root of the mean square value over a specified window of time (Merletti, 1999; Delsys, Inc., 2017). According De Luca (1997), RMS analysis quantifies the intensity

and duration of the muscle contraction, and provides a useful measurement of the signal amplitude that is easily analyzable. Using Delsys EMG Works Analysis software, the RMS window length and the window overlap can be specified according to the data set. Root mean square calculations have been used in previous physiology and biomechanics research on cross-country skiing, walking, and running, which are all sagittal plane activities comparable to splitboarding. In 2006, Zory, Millet, Schena, Bortolan, & Rouard used RMS calculations to measure fatigue in cross-country skiers during a series of three 1200m sprints. Zory et al. found a significant decrease in muscle activity in the biceps femoris and rectus femoris after the last sprint. An exhaustive investigation revealed that EMG has never been measured during uphill splitboard travel. There are many factors to consider that can influence the quality, recording, and analysis of an EMG signal.

Electromyography is susceptible to interference from numerous internal and external factors that can affect the quality of the recorded signal. De Luca (1997) has categorized the factors that influence EMG into three categories: causative, intermediate, and deterministic. Causative factors have a basic effect on the signal; deterministic factors have “a direct bearing on the information in the EMG signal and the recorded force” (De Luca, 1997); and intermediate factors that are both causative and deterministic. Extrinsic causative factors that affect the amplitude, frequency, or crosstalk of an EMG signal include the configuration of the electrode (the area and shape of the detection surface), location of the electrode with respect to motor points on the muscle and the muscle itself, and orientation of detection surfaces with respect to muscle fibers. Intrinsic causative factors include the number of active motor units (MU) at any point in time, fiber type composition of the muscle, blood flow of the muscle, muscle fiber

diameter, depth and location of active fibers, and the amount of tissue between the muscle and electrode. De Luca's intermediate factors that may affect the EMG signal are the filtering aspects and detection volume of the electrode, cross talk from nearby muscles, conduction velocity of action potentials (AP), and spatial filtering due to the position of the electrode relative to the active muscle fibers. The deterministic factors that can influence EMG signal information are the number of active MU, MU twitch force, MU firing rate, recruitment stability of MU, mechanical interactions between muscle fibers, and the amplitude, duration, and shape of MU APs. Despite these limitations, EMG has been found to be a reliable tool to measure muscle activity.

Stride Length

The physiological implications of variations in stride length have not been studied extensively in cross-country skiers, backcountry skiers, or splitboarders. In a recent study by Praz et al., (2016), ski mountaineers touring uphill on skis with climbing skins had a shorter stride length at steeper inclines. The longest stride length was found at a 7% grade, while the smallest was at a 33% grade. Praz et al. found that a self-selected speed allowed the user to self-select a stride that made uphill travel easier and more efficient. Additionally, the researchers found a significant relationship between stride length and oxygen uptake, measured as VO_2 . Using the equation for net efficiency, Praz et al. calculated metabolic energy expenditure by subtracting energy expenditure at rest from oxygen uptake at a given work load.

In runners, freely-chosen stride length is a function of body height and leg length, and is usually the most physiologically efficient for that person (Elliot & Blanksby,

1979). Cavanaugh and Williams (1982) varied stride length in runners by $\pm 20\%$, and found that variations from the freely chosen stride length resulted in a significant increase in oxygen consumption (VO_2), indicating that a naturally chosen stride is most physiologically efficient in highly trained runners. Oxygen consumption is commonly used to measure changes in physiological stress. Changes in stride length below $\pm 20\%$ had a wide range of effects depending on the individual. If restrictions of equipment are removed, splitboarders may be able to improve their energy expenditure while touring by self-selecting their stride length.

Kinematic Analysis

Motion capture technology has been used for biomechanical analysis on skiers and snowboarders in the field in previous research by McAlpine & Kersting (2006), Pellegrini et al. (2013), and Fasel (2016). This technology captures precise two- or three-dimensional data, and can be used to analyze kinematics. For splitboard touring, precise analysis of stride length and range of motion at the knee, and ankle are especially important.

Two-dimensional (2D) kinematic analysis can be a valuable and effective tool in situations when a three-dimensional (3D) analysis is not necessary. A video camera with sufficient resolution, shutter speed, aperture, and focus capabilities can be used to analyze motion in one plane or axis, and motion capture markers may or may not be utilized for video recording. In 2017, Schurr, Marshall, Resch, & Saliba compared sagittal plane 2D video analysis to 3D motion capture data during a single leg squat. Schurr et al. found moderate to strong relationships between the 2D and 3D analyses, and concluded that

“2D video analysis may be a more reasonable, inexpensive, and portable option [than 3D video analysis] for kinematic assessment” (Schurr et al., 2017). An increasingly popular software program used to process 2D motion capture data is the free and open-source program Kinovea (Kinovea, Boston, MA.). Kinovea (version 8.15.0) has been found to be valid and reliable for measurement of kinematic variables in vertical jumping (Balsalobre-Fernández, Tejero-González, Campo-Vecino, & Bavaresco, 2014), wrist range of motion (Abd El-Raheem, Kamel, & Ali, 2015), and running (Damsted, Nielsen, & Larsen, 2015).

Sagittal plane video analysis has been used extensively in walking and running to study lower limb joint kinematics. In 2015, Damsted et al. used two-dimensional sagittal plane video analysis to measure knee and hip joint angles on treadmill runners in a rehabilitation setting. Damsted et al. found high intra- and inter rater reliability of 2D analysis of the knee and hip angles in runners, but note that day-to-day variation in set-up can cause changes in measurement up to 8° within day, and 14° between days. McIntosh, Beatty, Dwan, & Vickers (2006) studied the gait of subjects walking on a treadmill at 0° , 5° , 8° and 10° of incline. The researchers found an increase in hip flexion at heel strike between inclines of -10° to $+10^{\circ}$, as well as increases in knee flexion and ankle dorsiflexion with an increased incline, but not a decline. Swanson & Caldwell (2000) also used sagittal plane video analysis to study the effects of high-speed incline and level treadmill running on lower body kinematics. Swanson & Caldwell found that stride frequency increased in incline running compared to level running, and also found that extensor range of motion of the hip, knee, and ankle joints was higher in incline running.

Although 2D kinematic analysis has proven to be reliable and useful in many research contexts, it has limitations that must be taken into consideration. Obvious limitations are the lack of information a 2D analysis can provide about movement in other planes of motion. A sagittal plane analysis provides no information about motion in the frontal or transverse planes. In a 3D motion capture system, a marker is usually captured by at least one camera at all times. In 2D motion capture, if a marker is blocked, there are no other cameras to find the marker's position from a different angle. In addition, 2D analysis is susceptible to parallax error, which occurs when motion does not occur perpendicular to the camera's field of view. While some programs can account for this distortion, a subject moving within the camera's field of view may not be perpendicular to the camera at all times. Finally, 2D video analysis quality is highly dependent on the video camera's resolution, shutter speed, frame rate, light sensitivity, and zoom.

Conclusion

The findings of this review indicate that no research has been performed on splitboard touring. While ski touring, walking, or classic cross country skiing may research may be used as an analog for splitboard movements, there are important fundamental differences, such as boot height, boot stiffness, and the presence of a ski that make splitboarding unique to these activities. Changes in stride length have been shown to have effects on energy expenditure, and lower-limb muscle activity and knee and ankle joint angles are expected to vary as stride length changes.

CHAPTER THREE

THE INFLUENCE OF SPLITBOARD BINDINGS AND TOURING-SPECIFIC
BOOTS ON MUSCLE ACTIVITY, STRIDE LENGTH, AND JOINT KINEMATICS
DURING SPLITBOARD TOURINGAbstract

Splitboarding is a form of alpine recreation that involves using a snowboard that splits into two skis to tour in backcountry terrain. At the summit, the skis are attached together and used as a normal snowboard to ride downhill. As splitboarding has grown in popularity, manufacturers have developed splitboard-specific equipment, such as bindings and boots. This crossover study investigated the effects of highback lean settings on Spark R&D splitboard bindings and two Burton Snowboards boot models while touring uphill. Subjects toured on a treadmill at a 10% incline in four test conditions: the Driver X boot with positive lean, the Driver X boot with negative lean, the Tourist boot with positive lean, and the Tourist boot with negative lean. Lower limb muscle activity was recorded as average root-mean-square (RMS) for gluteus medius (GM), biceps femoris (BF), rectus femoris (RF), medial gastrocnemius (MG), and tibialis anterior (TA). Kinematics variables of stride length, and ankle and knee range of motion (ROM) were also measured. The effects of the boots and bindings were determined using a two-way repeated measures analysis of variance ($\alpha < 0.05$). The main effect of binding on average RMS was not significant for all muscles except MG ($F = 8.821, p = 0.018, f = 1.05$), with the negative lean having higher average RMS than the positive lean. The main

effect of boot on stride length was significant ($F = 15.791, p = 0.003, f = 1.33$), with the Tourist resulting in a 3.56 cm longer stride length than the Driver X. The main effect of binding on stride length was also significant ($F = 9.875, p = 0.012, f = 1.05$), with negative lean resulting in a 2.21 cm longer stride length than the positive lean. The main effect of boot model on ankle ROM was significant ($F = 36.325, p = 0.000, f = 2.00$), with the Tourist having a larger ROM than the Driver X. There were no significant effects or interactions for knee ROM. The results of this study demonstrate that boot model and binding settings can affect biomechanical and physiological variables while splitboard touring.

Introduction

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Splitboarding is a type of snowboarding used to access backcountry terrain (Van Tilburg, 2000). A splitboard is a snowboard that can be divided longitudinally into two skis. When separated, the skis are used to tour uphill using a motion similar to backcountry skiing. During uphill touring, the heel of the binding is free, or unattached to the ski. The toe of the binding is attached to the ski using a pin or hinge system. At the

summit, the bindings are removed from the skis and re-attached horizontally to the board in a manner that clips the skis together, forming a snowboard. During descent, the splitboard functions as a normal snowboard. Splitboard sales have steadily increased from 2010 to 2014, which resulted in \$1.93 million in revenue in the 2014-15 season (SIA, 2015a; SIA, 2015b). At present, splitboarders are a small subset of snowboarders due to limitations imposed by cost and challenges of accessibility.

The biomechanical motion of touring uphill appears to be very similar to that of backcountry skiing and classic cross-country skiing. All methods of travel feature an unlocked heel, a locked toe, and use a combined stepping, lunging, and gliding motion to move uphill across the snow. A splitboard ski is generally shorter and wider than an alpine or cross-country ski. Snowboard boots are typically made of stiff fabric, while ski boots are made of hard plastic.

One of the primary goals of splitboarding is to access backcountry terrain that is unique, high-quality, and less accessible to the public. In an effort to improve the quality of improve backcountry touring, snowboard companies are developing products designed to make touring easier, more comfortable, and more efficient. The purpose of these products is to improve the splitboard experience so that the users are able to access more terrain while expending less energy. Historically, splitboarders have been limited to using binding systems that are bulky, heavy, and prone to malfunction. Spark R&D splitboard bindings are specifically designed to help splitboarders access backcountry terrain (Spark R&D, 2016).

Since 2015, Spark R&D bindings feature a “Rip and Flip Highback” (Figure 1.1). The highback is the vertical piece of the binding that provides support behind the calf and

posterior boot. The majority of snowboard bindings have a highback that is restricted to various amounts of positive (forward) lean, and that are not adjustable during use. On snowboard bindings, positive lean is designed to push user's ankle into slight dorsiflexion and provide support behind the calf. Spark R&D's bindings feature a highback that can be adjusted to provide support from +22° of positive lean to -13° of negative lean (Spark R&D, 2016). It is hypothesized that the negative lean setting allows for a greater range of motion at the hip, knee, and ankle, which may alter biomechanical and physiological function while touring. For example, the increased range of motion would allow the user to increase their stride length. In specific types of terrain, a longer stride may influence muscle activity, joint kinematics, and/or stride length. For example, while traversing across flat or low-incline terrain, a longer stride will allow for a splitboarder to decrease stride frequency while maintaining the same speed.

One hypothesized problem with negative lean is that many traditional snowboard boots do not allow for rearward flexion, which inhibits use of the full range of motion in Spark R&D bindings. To help resolve this issue, Spark R&D and Burton Snowboards have collaboratively designed the Burton Tourist – a snowboard boot specifically for splitboard touring that can take advantage of negative lean. The Burton Tourist boot has a similar design to the Driver X, which is one of Burton's stiffest and most popular backcountry boots (Figure 1.2). The two boot models feature the same outsole, but the Tourist has enhanced articulations at the ankle and calf that are hypothesized to allow for increased range of motion within the binding. However, if Tourist was to be used in a binding with positive lean only, it would be prevented from flexing rearwards. Use of the Tourist boot with Spark R&D bindings pairs two unique products that are designed to

help make splitboard touring more comfortable and efficient. The purpose of this study is to explore the relationships between the boot models, binding settings, physiology and biomechanics of the body while touring uphill. The effects and interactions of the Tourist boot and Rip and Flip highback have never formally been studied on human subjects.

Methodology

Informed Consent

The study protocol was approved by the Montana State University Institutional Review Board (IRB) prior to testing. All participants received verbal and written information regarding the purpose, protocol, risks, and benefits of this study prior to signing the informed consent. In order to participate in this study all participants were required to sign and submit the Informed Consent Form (Appendix A).

Subjects

The subjects for this study were experienced male backcountry splitboarders between the age of 18 and 45, who currently use Spark R&D bindings while touring. Subject anthropometric data can be found in Table 3.1. An *a priori* power analysis using G*Power version 3.1.9.2 (Erdfelder, Faul, & Buchner, 1996) indicated a sample size of 10 using an effect size of 0.5 and a power of 0.95. Non-probability sampling was used to recruit local splitboarders and associates of Spark R&D. Potential participants were contacted by email, word of mouth, or through advertisements. The participants were selected according to inclusion criteria.

	Age (years)	Height (cm)	Weight (kg)	Splitboarding experience (years)	VO ₂ max (ml/kg/min)
Mean	28.7	179.1	76.3	5.3	52.8
Standard Deviation	±4.9	±6.9	±4.6	±3.3	±7.5

Table 3.1 – Subject anthropometric data (n=10).

The inclusion criteria for this study were good overall health, at least one season splitboarding while using Spark R&D bindings, and a snowboard boots size that is between a men's size 9 and 11. The inclusion criteria ensured participant familiarity with equipment, experience in splitboarding, and ease of set-up. The exclusion criteria for the study were recent traumatic or structural injury to the lower limbs or physical inability to tour on a splitboard for the required trials.

Experimental Design

The study design was a repeated-measures crossover, with all subjects participating in all of the experimental conditions. Qualified subjects came to the Movement Science Laboratory (MSL) for two visits. Before testing began, subjects were asked to sign the informed consent form. On the first visit, the subjects performed a running maximal oxygen uptake (VO₂max) test on a treadmill according to the Bruce Protocol. Heart rate was recorded throughout the VO₂max test. On the second visit, the subject used their own splitboard and poles to ensure equipment familiarity. The participant was then outfitted with a Polar RC3 heart rate monitor, EMG sensors, and motion capture markers. Finally, the subject was fitted with the appropriate boot while the researchers assembled the bindings, splitboard, and poles.

The subject was given an initial acclimation period to familiarize themselves with the equipment and treadmill. Once the subject reached steady state heart rate at 60% of their $VO_2\text{max}$ (HR60), the speed of the treadmill was recorded. The subject toured on the treadmill at a constant speed required to maintain $HR60 \pm 5$ beats per minute (bpm). Once at HR60, all data was collected simultaneously for 60 seconds. The subject proceeded through the four test conditions (Table 3.2) until testing was complete. Subjects were asked to return to the MSL for the second session of testing between three and 14 days after completion of the $VO_2\text{max}$ test, depending on the subject's and MSL availability.

Stage	Binding position	Boot
D+	Positive	Driver X
D-	Negative	Driver X
T+	Positive	Tourist
T-	Negative	Tourist

Table 3.2 – The four test conditions. Incline remained constant throughout the stages, but speed was determined by the subject's heart rate. Order of the test conditions was randomized for each subject.

The independent variables were the position of the binding highback (positive/negative lean), and boot type (Driver X or Tourist). The dependent variables were lower limb muscle activity (mV), stride length (cm), and range of motion at knee and ankle (degrees). All testing was conducted at a 10% incline on a 3.5 m by 3.5 m treadmill.

Protocols: First Visit

VO₂max testing. To determine the experimental work rate (HR at 60% VO₂max), subjects were asked to come into the MSL for a running VO₂max test. Before testing began, the subject's height and weight were recorded using a scale and tape measure. All subjects were fitted with a Polar RC3 heart rate monitor and watch. The chest strap was placed around the chest, with the sensor centered on the sternum. An electrode gel was placed on the terminals of the chest strap to improve conductivity.

Subjects wore comfortable gym clothing, and were allowed approximately five minutes to warm up on the treadmill at a self-selected speed. After warmup, the VO₂max protocols were explained in detail to the participant. Next, the subject was fitted with a nose clip and one-way mask, which was connected to a Parvomedics TrueOne 2400 Metabolic Cart (Parvomedics Inc., Salt Lake City, UT). Heart rate was recorded using a Polar RC3 heart rate monitor and watch throughout VO₂max testing (see Appendix B for VO₂max data collection sheet). The subject was directed to complete the test until exhaustion, but the physiological criteria used to determine VO₂max were 1) a plateau in VO₂ despite an increase in workload, and 2) a respiratory exchange ratio (RER) above 1.10. Testing was conducted according to the Bruce Protocol (Bruce Kusumi, & Hosmer, 1973) (Table 3.3). Heart rate was recorded every 90 seconds throughout the test. After completion of the test, heart rate at 60% of VO₂max (HR60) was calculated and recorded.

Stage	Time (min)	Speed (mph)	Incline (%)
1	0	1.7	10
2	3	2.5	12
3	6	3.4	14
4	9	4.2	16
5	12	5.0	18
6	15	5.5	20
7	18	6.0	22
8	21	6.5	24
9	24	7.0	26
10	27	7.5	28

Table 3.3 – The Bruce protocol for VO₂max testing

Researchers calculated HR60 by graphing VO₂ and heart rate during the VO₂max test. A linear trend line was generated using the data points, and the equation for that line used to calculate the heart rate at 60% of VO₂max. Details for this calculation are shown in Appendix C. Following successful completion of the VO₂max test, subjects were asked to return to the MSL for a second visit. During this visit, EMG and kinematic were recorded while splitboarding on the treadmill.

Protocols: Second Visit

Initial Setup. Before data collection began during the second visit, the subjects were outfitted with EMG sensors and kinematic markers. The subject arrived to the laboratory wearing dark-colored and tight-fitting compression shorts or pants of their choosing. The subject also wore ski socks and a dark-colored t-shirt. The only equipment the subject was required to bring was their splitboard and poles, which were assembled by researchers familiar with splitboard equipment. The poles were set to the subject's

desired length, and any reflective markings were covered in non-reflective tape. The equipment provided for testing was a pair of Spark R&D Arc bindings (Spark R&D, Bozeman, MT) and Burton (Burton Snowboards, Burlington, VT) Tourist and Driver X boots. The bindings were available in size medium or large, and the boots were available in a men's US size 9, 10, and 11. Subjects selected the boot size that fit them most comfortably, and the bindings were fit according to the boot size.

Heart Rate. All subjects were fitted with a Polar RC3 heart rate monitor and watch (Polar Electro Inc., Lake Success, NY). The chest strap was centered on the subject's chest, just below the nipples. An electrode gel was placed on the terminals of the chest strap to improve conductivity. The Polar watch was secured to the handles on the frame of the treadmill directly in front of the subject.

Electromyography Setup and Collection. The EMG sensors used in data collection were Delsys Trigno surface EMG sensor (Delsys, Boston, MA). The Trigno EMG sensors are rectangular, single differential, parallel-bar, 276 x 241 x 127 mm, and have a common mode rejection ratio of -92 dB, an input impedance of $>10^{15}\Omega//0.2\text{pF}$, Ag/AgCl electrodes and triaxial accelerometers. Before the EMG sensors were placed on to the subject, the sensors locations were identified and marked on the belly of the muscle according to guidelines outlined by Mesin et al. (2009). The sensor locations were then cleaned with an alcohol wipe and a small patch of hair was shaved to allow for sensor placement directly onto the skin. Delsys EMG sensors were placed on the following muscles: tibialis anterior (TA), medial head of gastrocnemius (MG), biceps femoris (BF), rectus femoris (RF), and gluteus medius (GM). The sensors were placed using an

adhesive patch, and were also taped directly onto the skin. The placement of the sensors was checked for security, and the quality of the signal was checked on the computer. Sensor placements were adjusted as necessary in order to maintain a clean and consistent signal.

Electromyography data was collected at a sampling rate of 1926 Hz, and accelerometer data was collected from the vertical (Z) axis of the tibialis anterior sensor, and was recorded at 148 Hz. Electromyography and accelerometer data was recorded for 60 seconds using Delsys EMG Works Acquisition software (version 4.3.1).

Kinematic Setup and Collection. Once the EMG sensors were in place, the subject was fitted with four 14.0mm reflective motion capture markers. These markers were placed on the following landmarks on the right leg of all subjects: greater trochanter of femur (on top of compression pants or shorts), lateral femoral epicondyle, lateral malleolus (on top of snowboard boot), and on the toe of the snowboard boot. Markers were fixed to the hip and knee using round double-sided adhesive collars and black kinesiotape to prevent them from falling off due to sweat. Markers were fixed to the snowboard boot using round adhesives black duct tape.

A Sony AXF3 HDR Handycam video camera was used to record kinematic data. The camera was fastened to a tripod approximately three meters away from the subject's location, facing the subject's sagittal plane. Before data collection began, the camera's position and zoom were adjusted to ensure that the subject and equipment fit into the field of view. The camera recorded at 500 frames per second, while the focus and

brightness were adjusted manually. Orange tape on the frame of the treadmill outlined the area where the subject was instructed to tour, and kept them in the camera's field of view.

Procedures. After setup was complete, the subject put on the splitboard and was given an initial acclimation period on the treadmill to familiarize themselves with the equipment and treadmill. Once the subject reached HR60 during the acclimation period, the speed of the treadmill was recorded. At this point, the subject began the first of four test conditions. The subject toured on the treadmill at the constant speed required to maintain a steady state heart rate at $HR60 \pm 5$ beats per minute (bpm). The speed of the treadmill remained constant within each stage. Once the subject reached HR60, all data was collected simultaneously for 60 seconds. All data analysis was performed on 15 strides beginning at the 30 second mark of each 60 second trial in order to ensure that the subject had adequate adaptation time to the data collection procedures and equipment. Once data recording was complete, the treadmill was stopped, and the equipment was adjusted for the next stage. The subject proceeded through the four test conditions (Table 3.2) until testing was complete.

Data Analysis

Electromyography Analysis. Electromyography data was analyzed using Delsys EMG Works Analysis (version 4.3.1) and Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA). All EMG data was filtered using a 2nd order Butterworth band pass filter with a cutoff frequencies of 20 Hz and 400 Hz. Electromyography data was analyzed using a Root Mean Square (RMS) function. Root Mean Square values represent the average RMS signal for a given muscle within a stride cycle. The RMS window length

was 0.125 seconds and window overlap was 0.625 seconds (Doucet & Mettler, 2013; Jeffries et al., 2015; Lockie & Schultz, 2015). In 2014, Burden, Lewis, & Willcox (2014) analyzed the effects of manipulating RMS window lengths of 0.01, 0.15, 0.2, 0.25 and one seconds, with no overlap and overlaps of 25, 50 and 75% of window lengths. The researchers found that effect of manipulating window length was greater for peak EMG than mean EMG, with the one second window having the lowest variability. In addition, there was not statistical significance from manipulating the window length,

Stride Length. Average stride length was determined from analysis of 15 consecutive stride using EMG Works Analysis. Beginning at the 30 second mark of each trial, 15 strides were defined and isolated as the time from foot-strike of the right foot to foot-strike of the right foot again. The time of foot-strike was determined using the vertical (Z) axis on the accelerometer of the TA EMG sensor. The timing of foot strike was initially determined using visual analysis of a splitboarder on the treadmill matched to the accelerometer data. The timing of foot strike was confirmed using a comparison to the BF EMG signal.

In order to confirm the timing of foot strike in the accelerometer signal, the assumed timing of the foot strike was compared to the muscle activity of BF. A visualization of the walking gait cycle can be found in Figure 3.1, and will be used as a reference for the remainder of this section. During analysis of stride length, it was assumed that a walking gait was generally analogous to a splitboard touring stride in terms of muscle activation. In walking, BF is most active during late swing phase and heel strike in order to eccentrically control hip flexion (Ivanenko, Poppele, & Lacquaniti, 2004; Winter & Yack, 1986). In this splitboarding study, TA accelerometer data (Figure

3.2, top) was visually analyzed for timing of foot strike, and labeled using the pink and orange vertical lines. The window between the pink and orange lines represents the time from foot strike to foot strike. The same time window was overlaid onto BF EMG data (Figure 3.2, bottom). The timing of BF muscle activity in reference to the gait cycle was in agreement with the findings of Winter & Yack (2004) and Ivanenko et al. (2004), and was used to validate use of the accelerometer data to determine timing of foot strike.

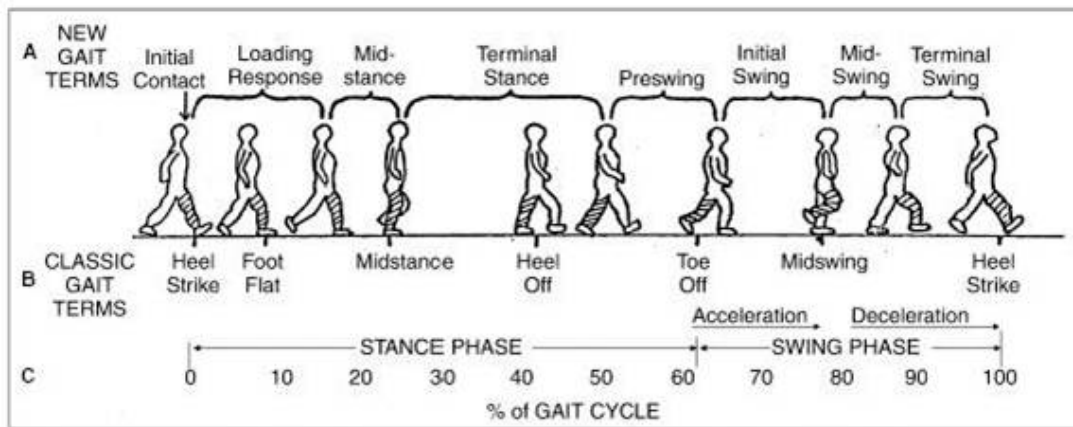


Figure 3.1– An illustration of the phases of a walking gait. Image from Uustal & Baerga, 2004.

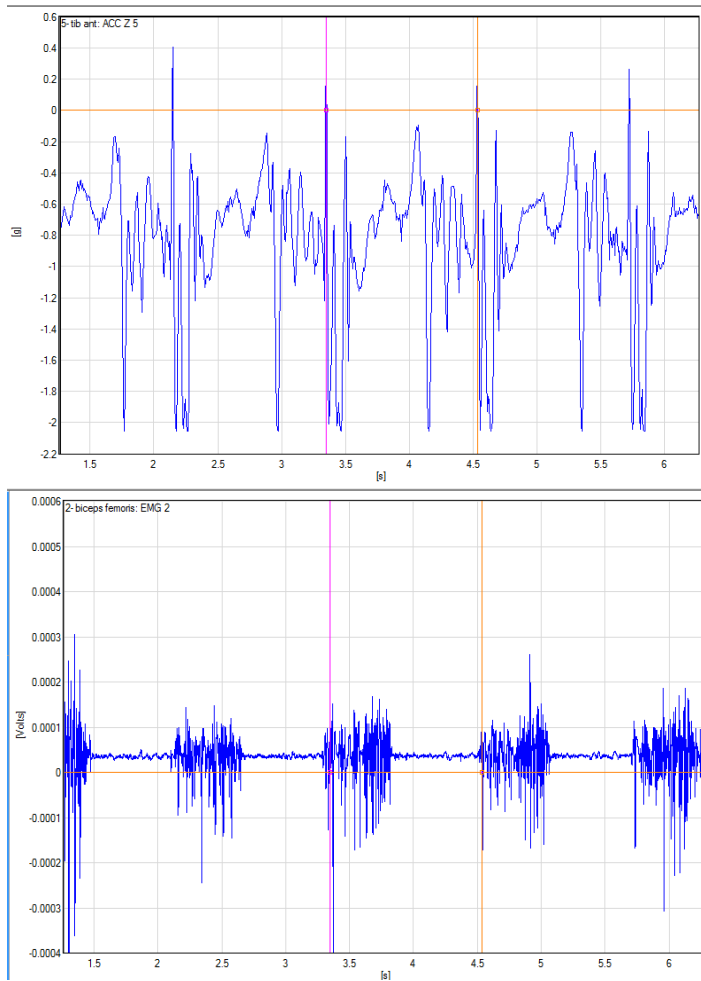


Figure 3.2 – Top: Vertical axis accelerometer data from the TA EMG sensor. Bottom: Biceps femoris EMG signal from the same point in time.

After isolation of individual strides, stride length was calculated using the velocity and stride frequency of each subject from EMG and accelerometer data. The stride length calculation was performed using the equation:

$$\text{stride length} = \frac{\text{velocity}}{\text{stride frequency}}$$

Stride frequency (strides per second) was determined by dividing 15 by the time required for fifteen consecutive strides. The subject's velocity in cm/s was divided by the time interval for one complete stride cycle.

Kinematic Analysis. Kinematic data was processed using Kinovea (Association Kinovea, France) version 8.25.0. Kinematic data was analyzed using Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) and MATLAB version R2016a (The Mathworks Inc., Natick, MA). Beginning at the 30 second mark of each trial, 15 stride strides were defined and isolated as the time from foot-strike of the right foot to foot-strike of the right foot again. Kinematic data was processed using Kinovea's autotracker, which uses a threshold algorithm to track the motion capture markers. Tracking errors were corrected manually. When markers were blocked from the camera's view by a hand or pole, manual frame-by-frame tracking was used. Joint angles were calculated by creating vectors between the marker coordinate points. The vectors represented the foot (between toe and ankle), the shank (between ankle and knee), and thigh (between knee and hip). Joint angles were then calculated using the law of cosines based on the vectors. Next, the joint angles were graphed, and the stride strides were isolated using the minimum and maximum joint angle points. A visualization of ankle and knee joint angles compared to phases of the splitboard gait cycle can be found in Figure 3.3. Range of motion (ROM) was defined as the difference between the local maximum and minimum joint angles within a given stride, and was reported in degrees. Data was smoothed using a moving average filter in Microsoft Excel prior to ROM calculation.

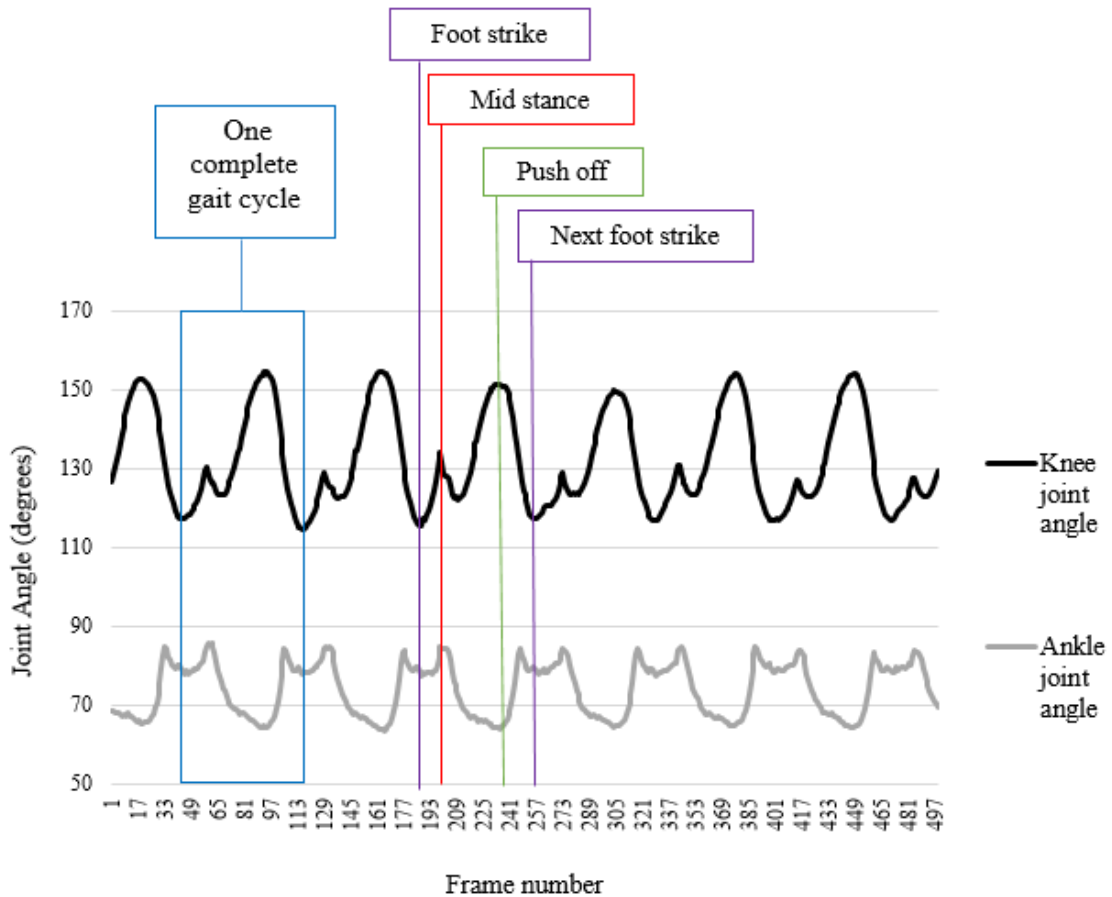


Figure 3.3 – The phases of the splitboard gait cycle compared to ankle and knee joint angles during uphill touring. Detailed descriptions of each gait phase can be found in Table 2.1. This figure shows six complete gait cycles from foot strike to foot strike.

Statistical Analysis

Statistical Analysis was performed using SPSS (IBM, Armonk, NY) version 22.0.0. A 2 x 2 two-way repeated measures analysis of variance (ANOVA) (α level of 0.05) was utilized for processing average RMS, stride length, and joint ROM. This study was a within-subject crossover design, and the test conditions were counterbalanced for all subjects. All statistics are reported as mean \pm standard deviation (SD). Effect size was calculated as Cohen's f using G*Power and partial eta squared values from SPSS outputs. Coefficients of variation and correlation analyses were performed using Microsoft Excel.

Results

Electromyography

A two-way repeated measures ANOVA ($\alpha < 0.05$) was conducted on the influence of boot model and binding setting on muscle activity measured as average RMS. Due to technical malfunction, EMG data was not recorded for Subject 7. In addition, GM data was not recorded for Subject 3. There was no boot by binding interaction for average RMS for GM ($F = 1.459, p = 0.266, f = 0.46$), BF ($F = 0.260, p = 0.624, f = 0.18$), MG ($F = 3.747, p = 0.089, f = 0.68$), or TA ($F = 0.006, p = 0.938, f = 0.03$). There was a significant boot by binding interaction for average RMS for RF ($F = 10.371, p = 0.012, f = 1.14$). However, inspection of pairwise comparison revealed no significant differences between boots (Driver X [$p = 0.372$]; Tourist [$p = 0.102$]) or binding setting (positive lean [$p = 0.091$]; negative lean [$p = 0.912$]). The main effect of boot on average RMS was not significant for all muscles: GM ($F = 1.750, p = 0.277, f = 0.50$), BF ($F = 0.984, p = 0.350, f = 0.35$), RF ($F = 1.253, p = 0.295, f = 0.40$), MG ($F = 4.041, p = 0.079, f = 0.71$), TA ($F = 0.061, p = 0.812, f = 0.09$). The main effect of binding on average RMS was not significant for GM ($F = 5.078, p = 0.059, f = 0.85$), BF ($F = 0.817, p = 0.393, f = 0.32$), RF ($F = 0.042, p = 0.843, f = 0.07$), and TA ($F = 0.090, p = 0.772, f = 0.11$). The main effect of binding on average RMS was significant for MG ($F = 8.821, p = 0.018, f = 1.05$), with negative lean having higher average RMS than positive lean. Individual EMG results for MG and TA can be found in Figure 3.7 and Figure 3.8, respectively. Descriptive statistics for all EMG results can be found in Table 3.5.

Muscle abbreviation	Muscle name	Test condition	Test condition description
GM	Gluteus medius	D+	Driver X, positive lean
BF	Biceps femoris	D-	Driver X, negative lean
RF	Rectus femoris	T+	Tourist, positive lean
MG	Medial gastrocnemius	T-	Tourist, negative lean
TA	Tibialis anterior		

Table 3.4 - Legend for all tables and graphs.

			Driver X			Tourist			Mean
			N	Mean (μ V)	SD	N	Mean (μ V)	SD	
GM	Binding	Positive	8	80.35	60.35	8	57.82	35.99	69.09
		Negative	8	56.24	36.49	8	74.37	55.09	65.31
		Mean	16	68.30	49.74	16	66.10	45.76	67.20
BF	Binding	Positive	9	47.44	7.28	9	47.17	7.23	47.31
		Negative	9	47.83	7.52	9	47.22	7.05	47.53
		Mean	18	47.63	7.18	18	47.20	6.93	47.42
RF	Binding	Positive	9	19.52	5.05	9	16.70	3.58	18.11
		Negative	9	18.38	3.92	9	18.23	5.04	18.30
		Mean	18	18.95	4.43	18	17.46	4.31	18.21
MG	Binding	Positive	9	67.61	25.44	9	73.07	27.19	70.34
		Negative	9	71.76	27.99	9	80.54	27.33	76.15
		Mean	18	69.68	36.03	18	76.80	26.73	73.24
TA	Binding	Positive	9	52.52	22.36	9	53.54	27.73	53.03
		Negative	9	53.48	21.09	9	54.09	23.05	53.78
		Mean	18	53.00	21.09	18	53.81	24.74	53.41

Table 3.5 – Descriptive statistics for EMG (reported as average RMS) results.

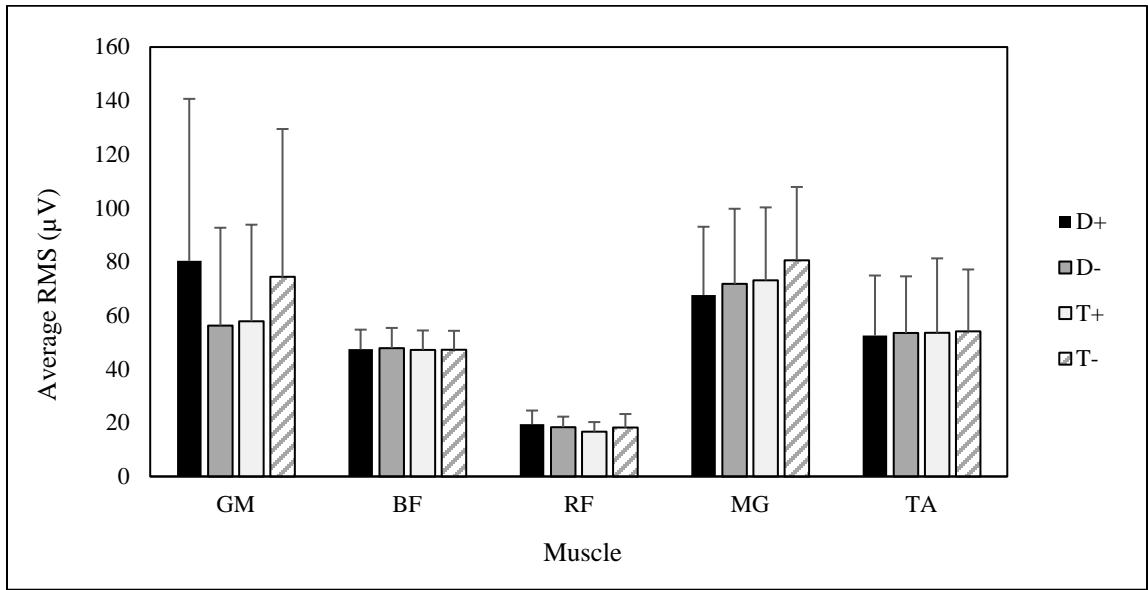


Figure 3.4 – Comparison of EMG (reported as average RMS) results (\pm SD) by test condition (n=9). For test condition and muscle name descriptions, see legend in Table 3.4.

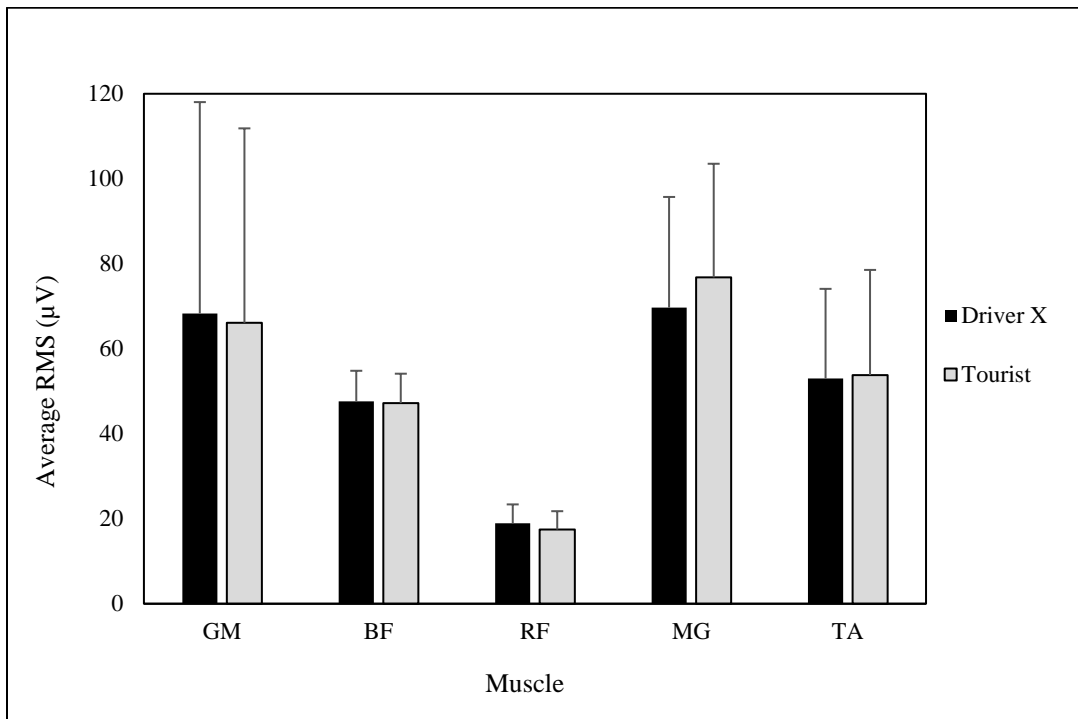


Figure 3.5 – Comparison of EMG (reported as average RMS) results (\pm SD) between boot models (n=9). For test condition and muscle name descriptions, see legend in Table 3.4.

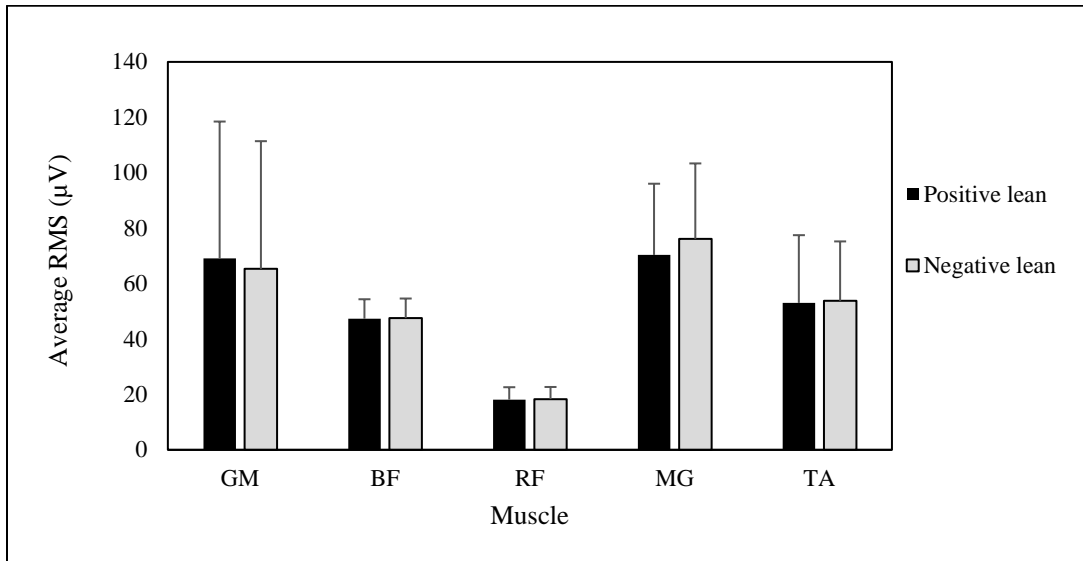


Figure 3.6 – Comparison of EMG (reported as average RMS) results (\pm SD) between binding settings (n=9). For test condition and muscle name descriptions, see legend in Table 3.4.

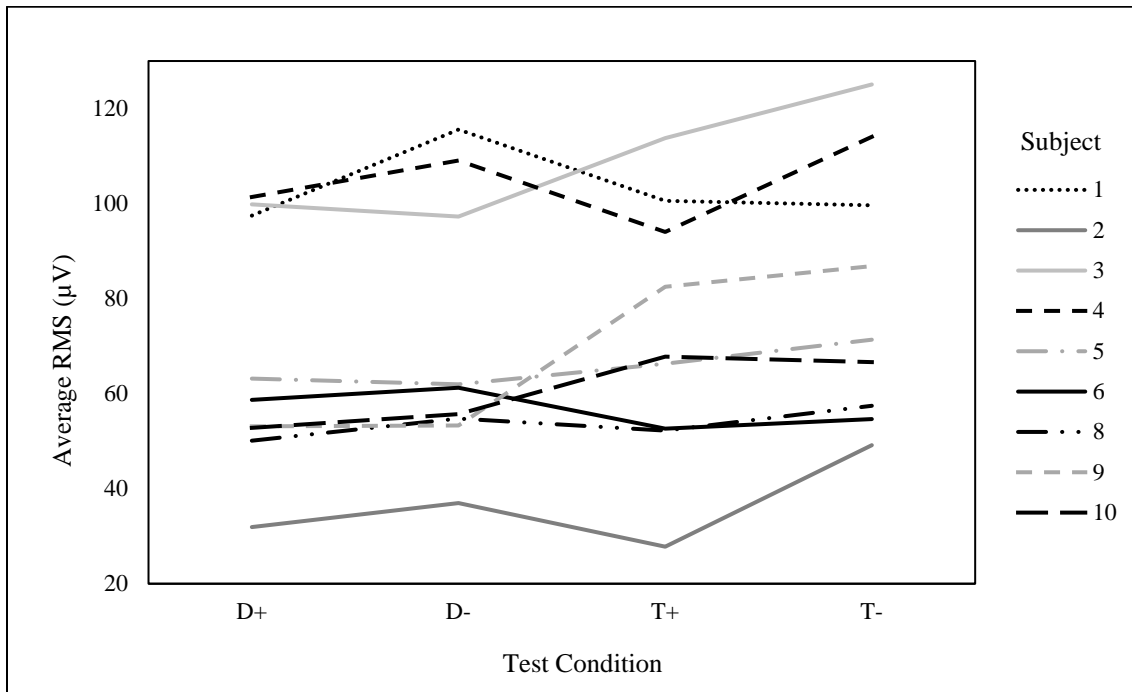


Figure 3.7 – Individual analysis of EMG results for MG (n = 9). EMG data was not recorded for Subject 7. For test condition descriptions, see legend in Table 3.4.

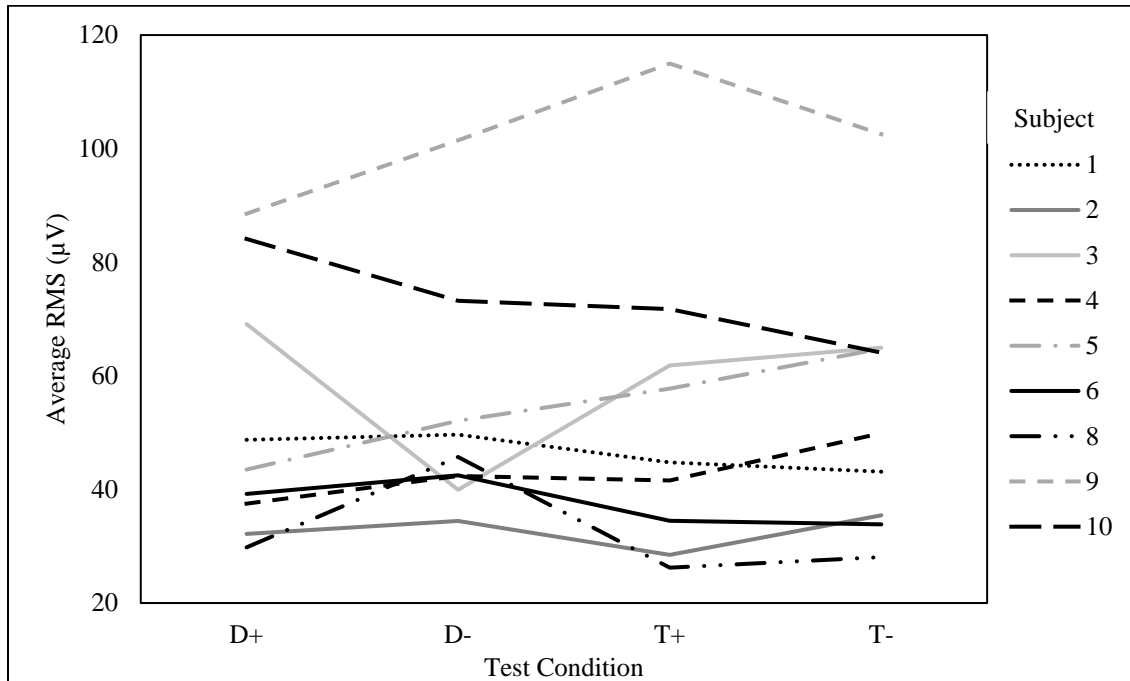


Figure 3.8 – Individual analysis of EMG results for TA (n = 9). EMG data was not recorded for Subject 7. For test condition descriptions, see legend in Table 3.4.

Stride Length

A two-way repeated measures ANOVA ($\alpha < 0.05$) was conducted on the influence of boot model and binding setting on stride length. There was no boot by binding interaction for stride length ($F = 0.675, p = 0.432, f = 0.274$). The main effect of boot on stride length was significant ($F = 15.791, p = 0.003, f = 1.325$), with the Tourist resulting in a 3.56 cm longer stride length than the Driver X. The main effect of binding on stride length was also significant ($F = 9.875, p = 0.012, f = 1.047$), with negative lean resulting in a 2.21 cm longer stride length than positive lean. Individual stride length results can be found in Figure 3.12. The coefficients of variation (CV) for each test condition, expressed as a percentage, were: D+ (2.78), D- (2.65), T+ (2.63), and T- (2.85). The correlation between the CV for each subject and years of splitboarding

experience was $r = -0.60$ (Figure 3.13). Descriptive statistics for all stride length results can be found in Table 3.6.

		Driver X			Tourist			Mean
		N	Mean (cm)	SD	N	Mean (cm)	SD	
Binding	Positive	10	145.4	9.8	10	148.4	11.6	146.9
	Negative	10	147.0	10.0	10	151.2	10.0	149.1
Mean		20	146.2	9.7	20	149.8	10.6	148.0

Table 3.6 – Stride length descriptive statistics.

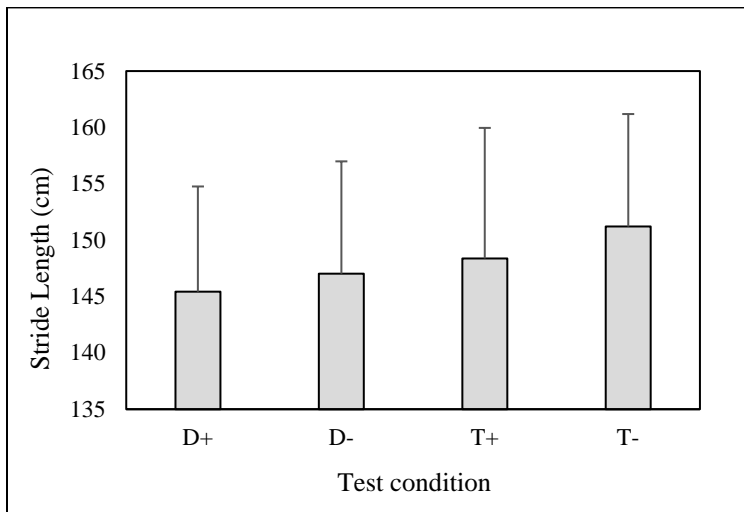


Figure 3.9 – Comparison of mean stride length (\pm SD) by test condition ($n=10$). For test condition descriptions, see legend in Table 3.4.

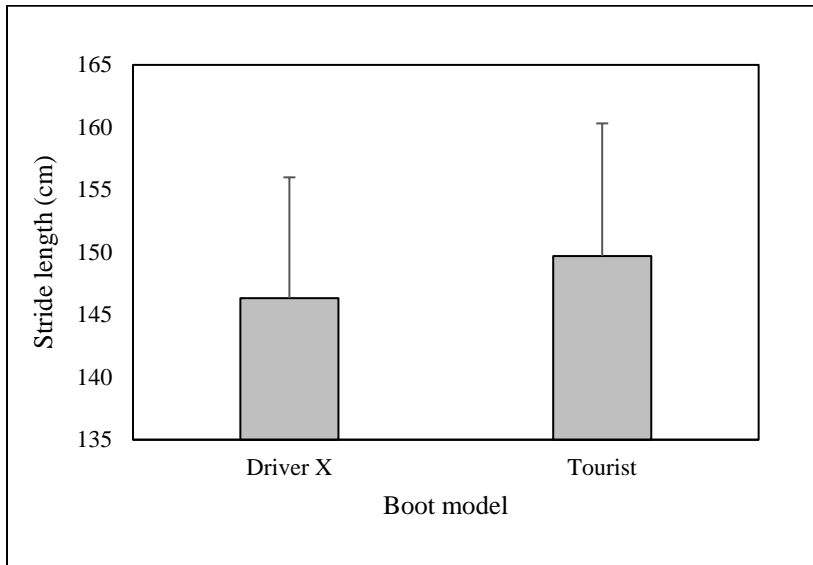


Figure 3.10 – Comparison of mean stride length (\pm SD) by boot model (n=10).

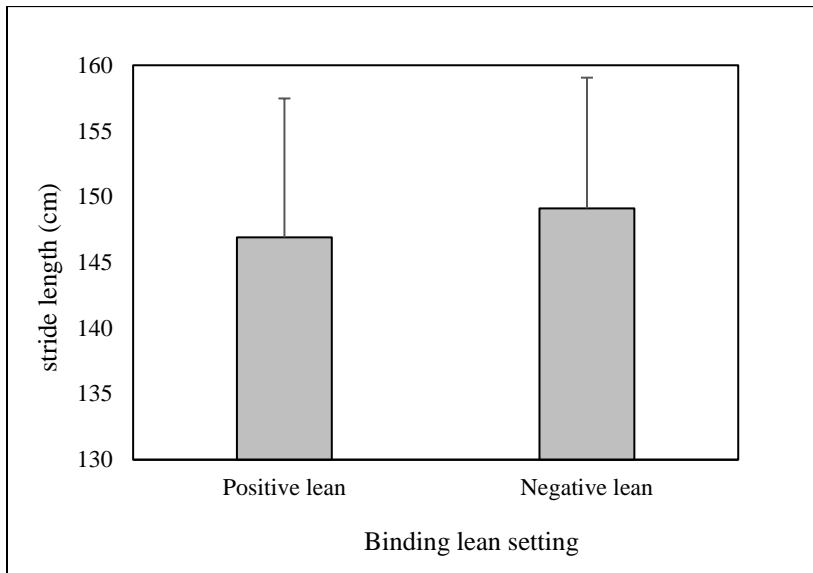


Figure 3.11 - Comparison of mean stride length (\pm SD) by binding setting (n=10).

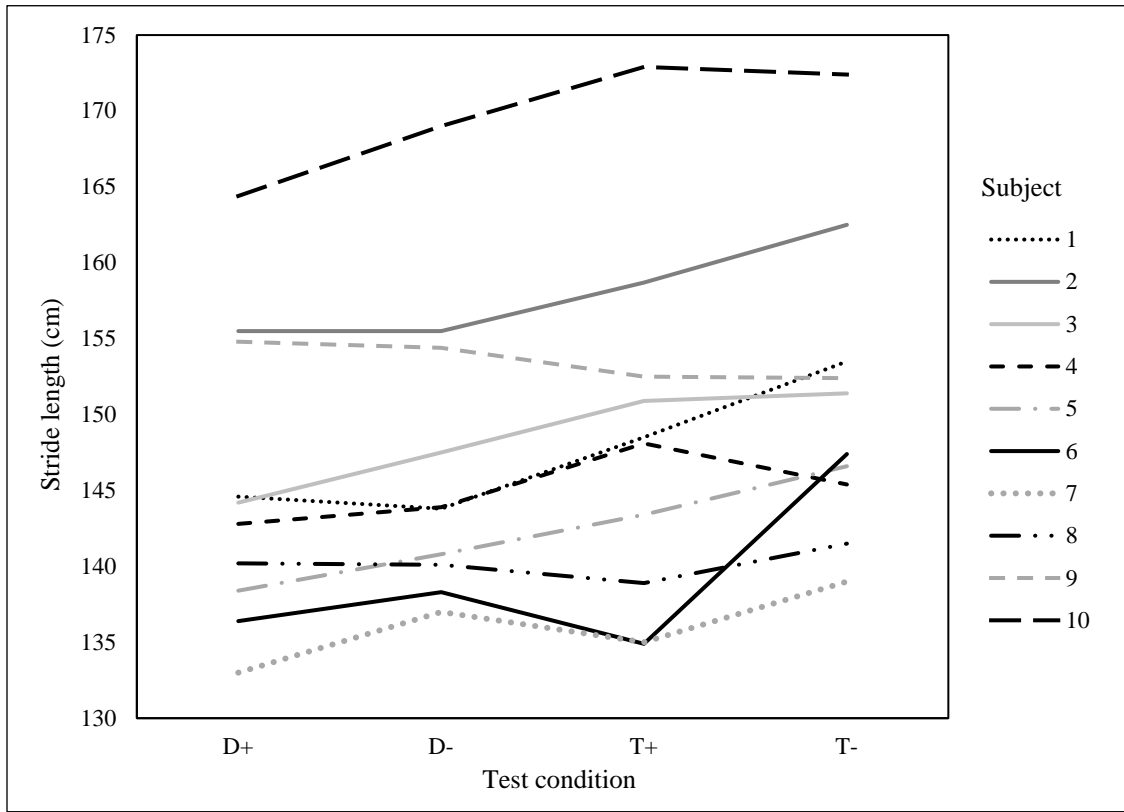


Figure 3.12 – Individual analysis of stride length results (n = 10). For test condition name descriptions, see legend in Table 3.4.

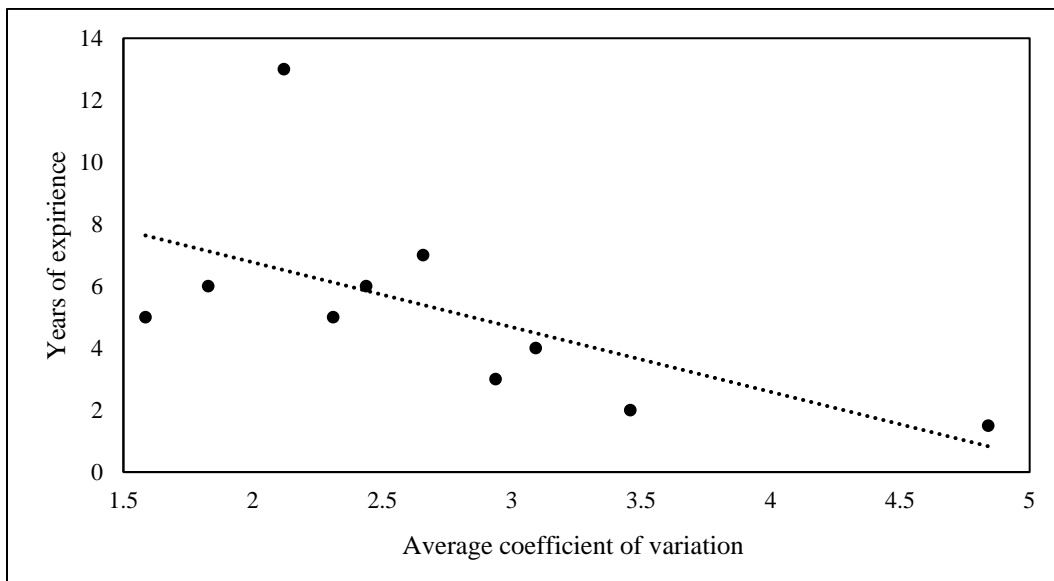


Figure 3.13 – Correlation analysis between years of splitboarding experience and stride length coefficient of variation for each subject (n=10).

Kinematic Analysis

A two-way repeated measures ANOVA ($\alpha < 0.05$) was conducted on the influence of boot model and binding setting on ankle and knee ROM. There was no boot by binding interaction for ankle ROM ($F = 2.997, p = 0.117, f = 0.057$) or knee ROM ($F = 0.072, p = 0.795, f = .090$). The main effect of boot on ankle ROM was significant ($F = 36.325, p = 0.000, f = 2.00$), with the Tourist having a larger ROM than the Driver X. The main effect of boot on knee ROM was not significant ($F = 0.326, p = 0.582, f = 0.201$). The main effect of binding was not significant for ankle ROM ($F = 0.791, p = 0.397, f = 0.296$) or knee ROM ($F = 0.812, p = 0.391, f = .301$). The coefficients of variation of ankle ROM for each test condition, expressed as a percentage, were: D+ (5.63), D- (6.09), T+ (6.19), and T- (5.83). All descriptive statistics for ankle and knee joint ROM (mean \pm SD) can be found in Table 3.7.

			Driver X			Tourist			Mean
			N	Mean (degrees)	SD	N	Mean (degrees)	SD	
Ankle ROM	Binding	Positive	10	20.43	2.87	10	21.91	2.14	21.17
		Negative	10	20.03	2.74	10	23.21	2.77	21.62
		Mean	20	20.22	2.74	20	22.56	2.50	21.40
Knee ROM	Binding	Positive	10	41.47	7.51	10	40.81	6.01	41.14
		Negative	10	42.00	7.12	10	41.77	7.23	41.88
		Mean	20	41.74	7.12	20	41.29	6.49	41.51

Table 3.7 –Ankle and knee ROM descriptive statistics.

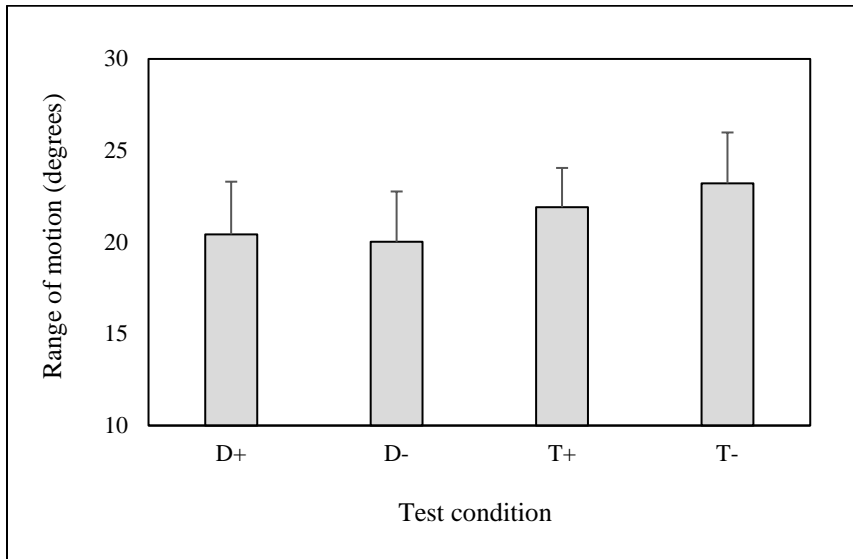


Figure 3.14 – Comparison of mean ankle range of motion (\pm SD) by test condition (n=10). For test condition name descriptions, see legend in Table 3.4.

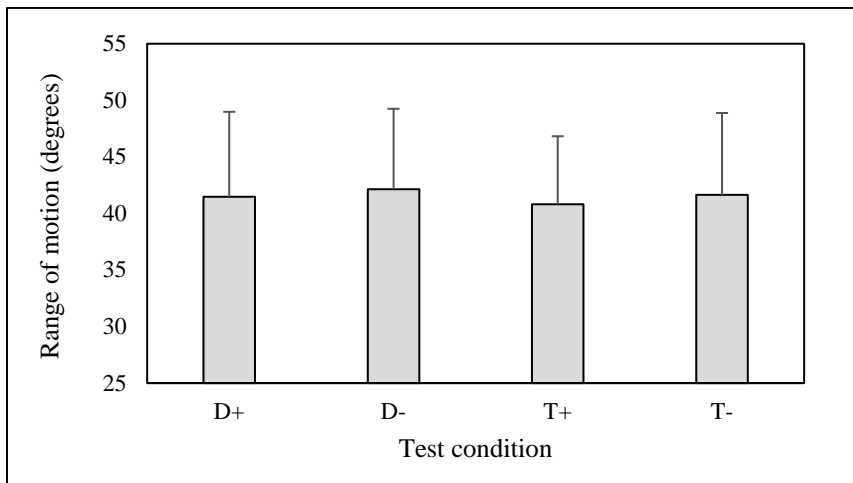


Figure 3.15 – Comparison of mean knee range of motion (\pm SD) by test condition (n=10). For test condition name descriptions, see legend in Table 3.4.

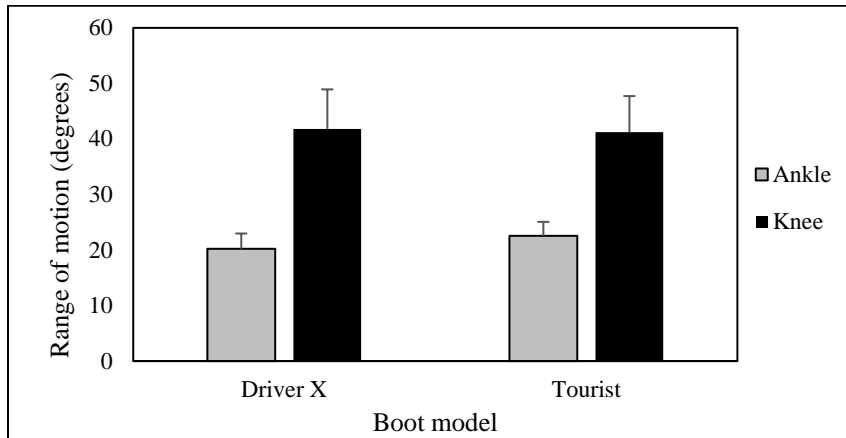


Figure 3.16 – Comparison of mean ankle and mean knee range of motion (\pm SD) by boot model (n=10).

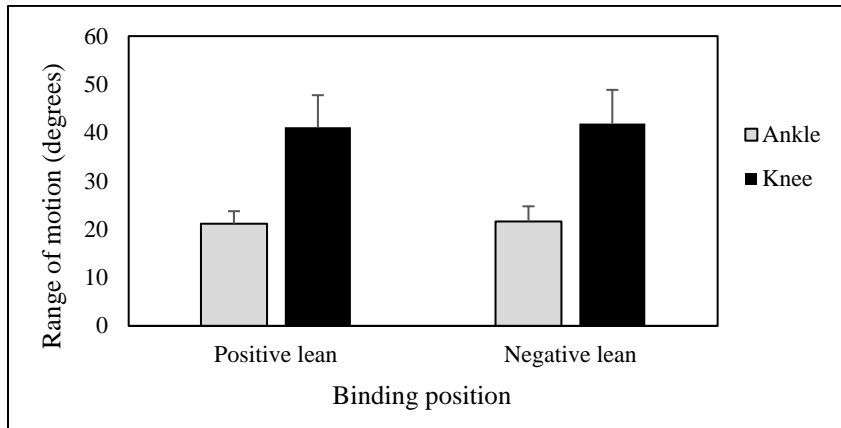


Figure 3.17 – Comparison of mean ankle and mean knee range of motion (\pm SD) by binding position (n=10).

Discussion

The purpose of this study to is explore the relationships between the Burton Tourist, Burton Driver X, lean settings on Spark R&D bindings, and their effects on physiology and biomechanics while touring uphill. Both the Tourist boot and negative lean significantly increased stride length. In addition, the Tourist increased range of motion at the ankle. Finally, use of negative lean increased muscle activity for MG. It is

important to note that these results apply only to the testing conditions and specific equipment used. This research is the first study to explore the effects of equipment during uphill splitboard touring. As a result, these findings establish a foundation for future research in this discipline, and present data for splitboard binding and boot manufacturers to use in research, development, and marketing.

Stride Length

The main effect of boot on stride length was significant ($F = 15.791, p = 0.003, f = 1.325$), with the Tourist resulting in a 3.56 cm longer stride length than the Driver X. This result may seem small over one stride, but splitboarders typically tour for many miles in order to reach the summit of their destination. One of the most popular beginner backcountry routes in Bozeman, MT, is the 4828 m long History Rock trail. Using data from this study, over the course of ascending this route once (assuming a constant speed and a constant incline of 10%), a subject using Tourist would theoretically take 3223 strides, while a subject using the Driver X would take 3303 strides. This difference of 76 strides (or 152 steps) is just for one lap on a relatively easy route. On more challenging and longer tours in the backcountry, this difference could be even larger.

The main effect of binding on stride length was also significant ($F = 9.875, p = 0.012, f = 1.047$), with negative lean resulting in a 2.21 cm longer stride length than positive lean. Using the same assumptions as above for one lap on the History Rock trail, use of the negative lean would theoretically take 3238 strides to the summit, while the positive lean would take 3287 strides. Use of negative lean would save 49 strides (or 98 steps) for one lap on this trail. Because the interaction of boot by binding on stride length

was not significant, it is not possible to quantify the combined effects of the Tourist and negative lean.

Consideration of individual variation is essential when interpreting these results. Figure 3.12, which shows individual results for stride length, highlights the different patterns that occurred between individuals. While most subjects increased their stride length between conditions D+ and T-, the patterns of change were not consistent. Despite the differences in Figure 3.12, the coefficient of variation for each test condition was less than three percent: D+ (2.78), D- (2.65), T+ (2.63), and T- (2.85). In addition, a correlation analysis was performed between a subject's splitboarding experience level (in years) and the individual subject's average CV over the four test conditions. The result, $r = -0.60$, indicates a moderate negative relationship between the variables (Figure 3.13). In general, subjects with more years of experience had a lower average CV. Conversely, subjects with less experience had higher CVs. Although a relationship exists, years of splitboarding experience is not the sole determinant of individual variation. Other factors, such as experience backcountry or cross-country skiing, fitness level, frequency of splitboard trips within a given year, and technical proficiency must all be taken into consideration.

As discussed by Tosi et al. (2010), backcountry skiers are most efficient when they are able to self-select a stride length. The stiffer Driver X boot and the more restrictive positive lean keep the ankle in a position of dorsiflexion. As a result of this limitation, users took shorter strides. These results demonstrate a problem common to many splitboarders who do not have splitboard-specific boots – a stiff, traditional snowboard boot that is built with natural positive lean is limited in rearward flexion. The

Tourist allowed for a longer stride length than the Driver X, but if used with positive lean, the Tourist would hypothetically be similarly limited in rearward flexion due to the inflexibility of the highback. Although the boot by binding interaction for stride length was not significant, there was a moderate effect size ($f = 0.27$). Further research is needed to evaluate the relationships between splitboard-specific boots and Spark R&D highback settings.

Kinematic Analysis

No significant interaction was found between boot model and binding setting for ankle or knee ROM. However, the Tourist did allow for an increased range of motion at the ankle compared to the Driver X ($p = .000$). This result can be explained by increased flexibility and articulation of the Tourist in both the forward and rearward directions. Regardless of the lean setting, the Tourist had a larger ROM than the Driver X simply due to its construction. It is important to note that the results of this study do not indicate the direction of the increase in ROM at the ankle. It is not known whether the Tourist allows for increased plantar flexion, dorsiflexion, or a combination of both. Although the main effects of binding on ROM were not significant, moderate effect sizes were found for the main effect of binding on ankle ROM ($f = 0.30$) and knee ROM ($f = 0.30$) (Cohen, 1969). The coefficients of variation of ankle ROM for each test condition, expressed as a percentage, were: D+ (5.63), D- (6.09), T+ (6.19), and T- (5.83).

Differences in ROM at the knee were negligible, with less than one degree of difference between all test conditions. The lack of significant differences at the knee suggests that either the change in ROM at the ankle was not great enough to influence the

knee, or that compensation could be occurring in a part of the body that was beyond the scope of this study. Compensation at the hip could be occurring, and could easily be measured by extending the sagittal plane analysis to include hip flexion and extension ROM. Compensation in the transverse and frontal planes are also possible, but quantification would require a 3D motion capture analysis.

The increase in ROM at the ankle due to the Tourist boot is important when considering pathologies related to limitations in ankle dorsiflexion. McIntosh et al. (2006) reported that during walking, as the angle of inclination increases from 0% to 18%, the amount of plantar flexion during toe-off and the amount of dorsiflexion during heel strike and loading response both increase. This response has not been studied in snowboarding boots, but snowboard boots limit ankle ROM more than the average shoe. Because of the tall cuff and stiff construction of snowboard boots, splitboarders are limited in their ROM at the ankle as they tour uphill. Potential pathological concerns relating to reduced ROM at the ankle include Achilles tendinitis (Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999), plantar fasciitis (Riddle, Pulisic, Pidcoe, & Johnson, 2003) and other compensatory movements at the subtalar and knee joints that may lead to development of patellofemoral pain syndrome (Piva, Goodnite, & Childs, 2005). The pathological concerns described above are all related to ROM being limited by internal factors, such as muscle stiffness. It is not yet clear what the long-term effects of externally-limited ROM may be. These effects could be investigated using a longitudinal study design, or through the use of motion capture analysis and inverse dynamics. More research is necessary to understand the pathological and biomechanical consequences of splitboard touring with limited ankle ROM.

Electromyography

At MG, negative lean resulted in significantly more muscle activity than positive lean ($F = 8.821, p = 0.018, f = 1.05$). In this discussion, a neutral ankle references the closed-chain anatomical position. Any posterior motion of the shank beyond the neutral position is considered plantar flexion, and any anterior motion of the shank beyond neutral is considered dorsiflexion. The increase in muscle activity at MG with negative lean could be due to the fact that negative lean allows the user to have a greater range of motion, particularly in plantar flexion. As muscle is moving across a greater range of motion, there is a larger amount of electrical activity within the muscle during that period of time. Conversely, when the muscle is moving through a smaller range of motion in the positive lean setting, there is less muscle activity. This result could be due to the fact that stretching a muscle results in greater EMG activity (Wilkinson, 1992).

There was no significant boot by binding interactions for average RMS for all muscles, however a trend was observed at RF ($p = 0.012$). An inspection of pairwise comparisons at RF revealed a trend for the Tourist ($p = 0.102, f = 0.40$) having larger average RMS values than the Driver X. According to Cohen (1969), the large effect size indicates that the Tourist may increase muscle activity at the RF. There is no statistical significance due to possible unknown confounding variables such as variability between subjects, body size, fitness level, or technical skill level. The role of RF in a walking gait is to extend the knee during swing phase and heel strike, to eccentrically control the knee during stance phase, and to flex the hip during swing phase. It is possible that the Tourist could cause an increase in muscle activity at RF due to the increased range of motion at

the ankle. However, the exact type of motion that is increased at the ankle (dorsiflexion vs plantar flexion) is not known based on the results of this study.

Although the remainder of EMG results were not significant, an analysis of individual EMG results revealed trends and effect sizes that are worthy of further investigation. Moderate effect sizes were found for the main effect of the boot on average RMS at BF ($f = 0.40$) and RF ($f = 0.40$) (Cohen, 1969). In addition, the main effect of binding on BF had a moderate effect size ($f = 0.32$). Large effect sizes were found for the interactions of boot by binding for GM ($f = 0.46$) and MG ($f = 0.68$) (Cohen, 1969). Large effect sizes were also found for the main effect of boot on GM ($f = 0.50$) and MG ($f = 0.71$), and for the main effect of binding on GM ($f = 0.85$). The amount of moderate and large effect sizes suggest that a type II error (incorrectly accepting the null hypothesis) could be occurring. It is possible that the study was underpowered or that a larger sample size is needed in order to better understand main effects and interactions for EMG.

Another analysis that warrants further investigation are the individual results from the EMG analysis. Figures 3.7 and 3.8 show muscle activity responses in MG and TA for all subjects. Individual patterns are observable in these figures that were not visible in the mean calculations (Figure 3.4). For example, Subject 5 is an intermediate-level splitboarder with 3 years of experience. In contrast, Subject 6 is an advanced/expert level snowboarder with 13 years of experience. The patterns of muscle recruitment are visibly different between these two subjects when they are sorted by experience level. While these two subjects cannot be held as representatives of all advanced and intermediate splitboarders, it does suggest that patterns of muscle activation may vary by

skill level. An investigation of all subjects at the individual level did not show consistent patterns when sorted by years of experience, but it is important to be cautious when associating years of experience with skill level without any technical skill evaluation. Further, the sample size of our study is too small to draw larger conclusions about the influence of skill level on EMG. Additionally, this example highlights one of the limitations of calculating a means across a group – less obvious trends and patterns can be lost without detailed investigation.

The results of this study are represent data collected over 15 strides that occurred within a five minute window of time. As a result, the results may not represent the influence of the boot and/or binding interface over longer distances. While RMS values may not have varied greatly across 15 strides, it is possible that muscle activity and fatigue patterns would change significantly in a field setting where the subject tours over many miles. Both Swanson & Caldwell (2000) and Wall-Scheffler et al. (2010) reported an increase in muscle activity while incline running, but tested subjects at steep slope angles (30% and 20%, respectively). Although this study did not compare splitboarders at different slope angles, it is also possible that a steeper incline is necessary to cause significant changes in muscle activity. However, splitboarding at steep inclines without the use of a riser is not realistic for most splitboarders. A longer period of data collection would not only be more realistic for applied splitboarding, but could be used to test muscular fatigue using EMG.

Limitations

It is important to acknowledge various limitations to this study that may have affected the results. The first limitation is that the subjects were touring indoors on a rubber treadmill surface. While the treadmill allowed for a highly controlled testing environment (speed, incline, temperature), the subjects were unable to glide on the rubber surface. A normal touring motion was possible, but on snow, a splitboarder is able to glide upon heel strike. While glide would have made measurements of stride/stride length much more complicated, it is important to note that the glide is an important facet of a splitboard stride. On low-incline climbs on snow, splitboarders are able to use the push off motion to propel themselves forward with a gliding motion because the ski slides against the snow. In the laboratory, this ability to glide was limited due to friction between the ski and the treadmill surface. The gliding motion allows the user to elongate their stride and stride length, while maintaining a low step frequency. By observation, as stride length increases (especially on lower inclines), the more a splitboarder is able to glide. The ability of a splitboarder to glide is also dependent on the equipment they are using. A binding restricted to positive lean would hypothetically keep the user in a position of ankle dorsiflexion, so they would be unable to plantar flex at heel strike to maximize their stride length. In addition, the stiffness of the boot could restrict the ability of the user to dorsiflex during the terminal stance preceding push-off. While subjects were able to acclimate to the treadmill surface quickly, it is likely that they had to modify their natural stride in order to accommodate the lack of glide.

Another important limitation to this study is the inherent variation within human subjects. Splitboarding is a relatively new sport, but is isolated to areas where

backcountry terrain is accessible in the winter. The recent increase in the number of splitboard clinics, demos, and festivals has helped spread information about splitboarding equipment and technique. However, many new splitboarders have limited experience with splitboard lessons or coaching. Splitboarding-specific instructors or guides are rare, and so most technical information is passed on informally through word of mouth or the internet. As a result of this new and developing community, splitboarders have a diverse range of technical skills with little formal instruction.

The subjects for this study were all recruited from Southwestern Montana, but had a relatively wide range of splitboarding experience (Table 3.1). All subjects were required to have been splitboarding for at least one year, but the high level of variance in the results suggests that there is a wide range of levels of technique. The lowest level of experience was 1.5 years, and the highest level of experience was 13 years. It is important to note that although subjects reported their experience level in years, there is a high level of variability to the number of days spent in the backcountry during each year. A few indicators of good splitboarding technique include consistent poling (opposing hand and foot), a smooth drag of the ski along the surface of the snow or treadmill during swing phase (as opposed to picking it up in a stepping motion), a consistent stride, and an ability to change step technique or stride length as the incline or snow surface changes.

Technical evaluations were not conducted during the study, but a subjective review of the video recorded during data collection indicated that the subject group contained a wide range of techniques and skill levels. Variations in skill, such as differences in poling technique, were not factored into the results of this study. In addition, the subject's personal preference for boot and binding type should be taken into consideration. Some

subjects preferred the Driver X due to its stiffness and responsiveness, while other subjects preferred the Tourist. Some of this variation could be due to familiarity with the products.

Finally, the technique of several subject's stride caused challenges capturing marker coordinates during video analysis. The motion capture marker placed on the greater trochanter of some subjects was blocked from the camera's field of view by the hand of the subject as they pushed off with their poles. Because the subjects were instructed to tour using their normal stride, they were not informed that their poling motion was blocking a marker. When the video was processed in Kinovea, sections of video existed where the motion capture marker was not visible. Researchers were able to estimate the position of the marker using anatomical landmarks, but the true location of the marker was not known. As a result, the position of the thigh vector used to calculate the knee joint angle was not as precise as the vectors used to calculate the ankle joint angle. This limitation may have contributed to the lack of significant interaction in knee joint ROM.

Future Research. The results of this research can be applied to research and development within splitboard binding and boot manufacturing. While the data from this study was analyzed over fifteen strides, moderate and large effect sizes in the results indicate that interaction of the boot and binding may be important with a larger sample size or over longer distances. Effective use of negative lean appears to require a boot that is able to flex rearward, but a flexible boot's ROM may be restricted by a binding without negative lean. Further, a touring-specific boot must also be an effective downhill

snowboarding boot. While plastic ski-touring boots are able to transition between “walk/tour” and “ski” modes, this technology is challenging to implement in snowboard boots because of the differences in construction materials. Data from this study could be used to inform the design of new snowboard boot features that are optimized for biomechanical efficiency. In addition, product research and development should focus on the interaction between the boot and binding in order to optimize the features of both products.

Future physiological research on splitboard touring can investigate the effects of touring in an outdoor environment over longer distances. A combination of VO_2 and EMG analyses could further understanding of how equipment affects energy expenditure. The effects of stride length are most apparent over longer distances, and it is possible that long-duration activity might affect muscle activity in terms of fatigue. Fatigue and energy expenditure are directly relatable to the average splitboarder, who are invested in understanding how they can properly utilize their equipment to tour further and longer.

Research performed on-snow would also allow for more realistic testing where the slope surface, speed, and incline are not consistent. On a typical splitboard tour, the snow surface can vary due to changes in temperature, snow density, moisture content, wind loading, and/or sun exposure. In addition, the slope incline varies naturally due to topography, and the user will subsequently adjust their stride according to the conditions. All of these environmental factors influence the interaction of the splitboard with the snow, and in turn how the user changes their stride. For example, on a steep approach a user might take smaller steps and apply pressure differently than on a flat approach where they may glide or skate with an elongated stride. A gliding stride could not only improve

stride length, but possibly increase velocity by increasing stride length and maintaining the same step frequency (velocity = stride length x stride frequency). In the laboratory, all of these factors were controlled to minimize external variables. In an outdoor research setting, it would be not only possible to understand how splitboard equipment functions with the human body on the mountain, but the equipment would be used in the context it was designed for.

Although results analyzed over a single stride indicated some differences and interactions between the test conditions, there are important implications for splitboarders. Use of an appropriate boot and binding combination, such as the Burton Tourist with the Spark R&D Bindings with negative lean, may have important physiological and biomechanical implications over longer distances. Previous research on skiers has shown that the ability to self-select a stride can help to mitigate metabolic costs, and future research could further investigate the effects of the Tourist and negative lean on stride frequency, energy expenditure, and fatigue.

Conclusion

In conclusion, the results of this study demonstrate that boot model and binding settings can affect biomechanical and physiological variables while splitboard touring. Both the Tourist boot and the negative lean setting significantly increased stride length. In addition, the negative lean setting resulted in an increase in muscle activity for MG. Finally, use of the Tourist also increased range of motion at the ankle. The applicability of these findings is important to splitboarders because of the possibility to decrease step frequency. During backcountry travel, splitboarders travel many miles to reach their

destination. Over long distances, the stride length savings due to use of the Tourist boot or negative lean become apparent. In addition, it is possible that the combination of the Tourist boot and negative lean setting may provide physiological and biomechanical advantages to the user. Future research should investigate how splitboard equipment affects stride frequency, muscular fatigue, and energy expenditure over the course of prolonged, outdoor tours.

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APPENDICES

APPENDIX A

INFORMED CONSENT FORM

SUBJECT CONSENT FORM FOR PARTICIPATION IN HUMAN
RESEARCH AT MONTANA STATE UNIVERSITY

Title: *The influence of forward and negative lean settings on a splitboard binding highback on lower limb muscle activity during touring.*

Investigator: Celine Valentin, Montana State University Movement Science/Human Performance Laboratory

Funding Agency: Spark R&D, Burton Snowboards

You have been invited to participate in a research study investigating changes in muscle activity while using the positive and negative lean settings on Spark R&D splitboard bindings.

Procedures

You will be asked to use your own splitboard, poles, and other accessories necessary for touring on your splitboard. You will be provided with Spark R&D Bindings, Burton Boots, and Spark R&D climbing skins to use during testing. All research will be conducted in the Movement Science Laboratory (MSL) at Montana State University.

Before data collection, you will be asked to complete a VO₂max test. The test is used to measure maximal aerobic oxygen consumption during exercise and is conducted on a treadmill in the laboratory. Before beginning, you will warm up for five minutes at a comfortable pace on a treadmill. Following warm-up, the test will begin, and consists of incremental stages that progressively increase in speed and grade. You will proceed through each successive stage until you have met specific physiological criteria that indicate that you have reached VO₂max, or until you have reached exhaustion. The test can be ended early in case of emergency, but will not last longer than 30 minutes.

You will meet at the Movement Science Laboratory (MSL) at Montana State University area to be fitted with surface electromyography sensors (sEMG), motion capture markers, and other instruments. EMG sensors will be fit according to manufacture instructions, using an alcohol prep pad to clean the skin surface. The sensor pad has self-stick adhesive to keep it in place. You will be asked to wear tight-fitting shorts for testing. If you have leg hair, a small 2x1 inch area will be shaved for placement of five sensors. The motion capture markers will be placed directly on the skin, and secured with athletic tape.

Sensors will be placed over various muscles of the hip and leg and may include the tibialis anterior, medial head of gastrocnemius, biceps femoris, rectus femoris, vastus medialis, and gluteus medius (see attached page for a labeled muscle diagram). Your equipment will be inspected to make sure that it is safe and properly fitted before testing. Finally, you will be fitted for boots to use during the experiment. After placement of the measuring devices and equipment inspection, you will warm up on the treadmill for five minutes to warm up your muscles and familiarize yourself with the testing equipment.

Following warm up, you will be asked to climb on the treadmill at a 5 degree incline for four trials. Each trail will last up to ten minutes and will feature a unique configuration of boot and binding setup, and you will be given a small break between trials. The speed at which you will splitboard on the treadmill is dependent on the results of your VO₂max test. Trials may be repeated in the event of equipment malfunction or human error. Verbal instructions will be provided to you between trials, and researchers will perform all equipment adjustments. You will be asked to keep your touring motion and stride as consistent as possible during and between trials.

Confidentiality

All data will be coded so that personal information will not be made public. However, you may be photographed or a video may be taken of you during the tests for use in presentations or for marketing purposes. You may elect to have your identity obscured in photographs and video. Personal information and data will be kept in a locked cabinet. Data used in analysis will be coded so that data sheets will not be identifiable.

Time Commitment

The time commitment for the first visit is less than one hour. The time required for the second visit may take up to two hours.

Benefits

Results from this study may be used for product research and development at Spark R&D and Burton Snowboards, marketing purposes, presentation at a scientific conference and/or publication in a scientific journal. Results will be provided to you for your education on how use of forward and negative lean while touring affects muscle activity and range of motion.

Compensation

There is no compensation available for participation in this study.

Risks

The risks of involvement in this study include fatigued muscles from the exercise and possibility of injury from a fall. Testing will occur at low speed walking pace (less than 3 mph) to minimize risk. We will do our best to minimize risks. Should emergency medical attention be required, standard protocol (calling 9-1-1), will be followed. Celine Valentin is a nationally and state certified Emergency Medical Technician and can provide care in the event of a medical emergency. There is no compensation available for this treatment.

Questions

Your decision whether or not to participate will not jeopardize your relationship with the MSU Movement Science/Human Performance Laboratory. You are free to discontinue participation at any time without adversely affecting your relationship with MSU, Spark R&D, Burton Snowboards, or the researchers. If you have any questions, please do not hesitate to ask. If you have any additional questions after participation in the study, please contact Celine Valentin (860-462-1927) or Dr. John Seifert (406-994-7154 or john.seifert@montana.edu).

Additional questions about the rights of human subjects can be answered by the Chairman of the Institutional Review Board, Dr. Mark Quinn, (406) 994-4707.

Freedom of Consent

I have been given ample opportunity to read this document in its entirety and to ask questions which have been answered to my satisfaction. I hereby consent to become a participant in this study knowing the health risks involved and that I may withdraw my consent at any time, for any reason. I am covered by a health insurance program. I also understand that project personnel may screen me from this study for any reason deemed appropriate. Such reasons may include abnormal physiological responses to exercise. I declare that I am fit, an experienced splitboarder, and that I am of the ability to safely complete this protocol.

AUTHORIZATION: I have read the above and understand the discomforts, inconvenience and risk of this study. I, _____ (*name of subject*), agree to participate in this research. I understand that I may later refuse to participate, and that I may withdraw from the study at any time. I have received a copy of this consent form for my own records.

Signed: _____

Witness: _____

Investigator: _____

Date: _____

APPENDIX B

VO₂ MAX DATA COLLECTION SHEET

Subject Name: _____ ID: _____ Date: _____

Age: _____ HR max (220- age): _____ Height: _____
 Weight: _____

VO2max end test criteria:

1. RER above 1.10
2. No change in VO₂ despite increase in workload
3. Monitor calculated HR max

Stage	Time (min)	Speed (mph)	Incline (%)	Heart rate (bpm)
1	0	1.7	10	
2	3	2.5	12	
3	6	3.4	14	
4	9	4.2	16	
5	12	5.0	18	
6	15	5.5	20	
7	18	6.0	22	
8	21	6.5	24	
9	24	7.0	26	
10	27	7.5	28	

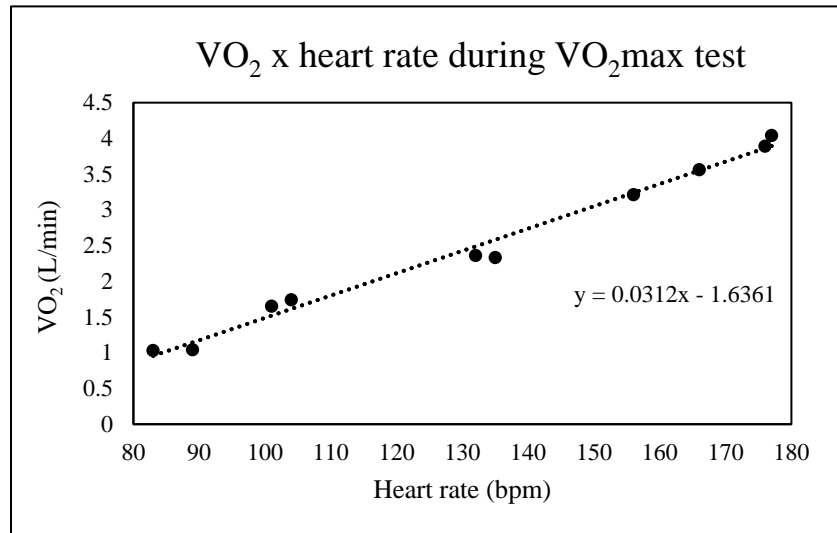
Test Notes:

APPENDIX C

SAMPLE CALCULATION OF HR60

Subject 1 heart rate data from VO₂max test

Heart Rate (bpm)	VO ₂ (L/min)
83	1.03
89	1.04
101	1.65
104	1.74
132	2.36
135	2.33
156	3.21
166	3.56
176	3.89
177	4.04



Linear trend line equation: $y = 0.0312x - 1.6361$

VO₂ max = 4.04 L/min

60% VO₂ max = 2.42 L/min

$$2.42 = 0.0312x - 1.6361$$

HR60 = 130 bpm

APPENDIX D

TESTING DATA COLLECTION SHEET

Subject Name: _____ ID: _____

Date: _____

Weight: _____ Boot size: _____

Calculated 60% HR: _____

HR test range: _____

STAGE	Incline	Speed	HR	BINDING	BOOT	NOTES
0	10%					Practice stage. Set camera focus manually. Determine speed for steady state HR60.
1	10%					Record all at HR60 for 60 seconds
2	10%					Record all at HR60 for 60 seconds
3	10%					Record all at HR60 for 60 seconds
4	10%					Record all at HR60 for 60 seconds

Test Notes: