Tribological Evaluation of Polymer Matrix Composites for Green Alternative Replacement in Alpine Sports: Scaling up between Laboratory and Field Testing

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Abstract

Tribological Evaluation of Polymer Matrix Composites for Green Alternative Replacement in Alpine Sports: Scaling up between Laboratory and Field Testing

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For ecological considerations, the International Ski Federation (FIS) has imposed a prohibition on the use of fluorinated waxes in ski and snowboard race preparation. Current substitutes exhibit inferior friction-reducing properties. This assessment aims to corroborate frictional performance in both laboratory-based evaluations and field trials. The evaluation employs a categorical approach, introducing incremental considerations for cost, lead time, and representativeness of actual competition conditions.

Traditional base material in snowboards, Ultra-High Molecular Weight Polyethylene (UHMWPE), serves as the baseline. Insights from aerospace investigations indicate that polymer composite structures with fibers aligned in the normal direction (NOFRC) exhibit performance in environments involving ice adhesion suggesting potential suitability for the cold and wet conditions characteristic of ski and snowboard competitions. Laboratory examinations include Scanning Electron Microscopy (SEM), confocal laser scanning microscopy (CLSM), tribometer tests utilizing a ball-on-disk linear tribometer (Anton-Paar TRB3 tribometer), contact angles, and time trials on High Density Polyethylene (HDPE) synthetic ice.

Field testing incorporates the use of inertial measurement units (IMUs) alongside 50-meter time trials conducted by athletes. Comparative analysis is conducted utilizing metrics such as surface energy, material composition, surface roughness values, coefficients of friction, and trial time. The findings reveal that, under conditions of dry friction and elevated temperatures, NOFRC demonstrates favorable tribological effects. However, UHMWPE emerges as the superior-performing material across all low temperatures and moisture instances. The consistency of categorical evaluations throughout the testing environments provides a valuable framework for appraising potential material alternatives for snowboard bases.

Acknowledgment

I would like to thank Dr. Pantcho Stoyanov for the opportunity to collaborate on this project, which aligns well with my passion for sports and engineering. This journey has taught me many things I am confident will positively impact my career and life from here.

I would like to thank Mr. David Jecker from INS for initiating this project. I thank Mr. Niko Desmarais and Mr. Blake Lewis for their expertise and assistance in conducting field studies with athletes. I would like to thank Boston Materials and for their support. Additionally, I would like to thank Mr. Rob Lu from Winterstick snowboards for his help in manufacturing the boards and industrial conversations. I would like to thank Ms. Marie Laurence-Cliché in addition to Mr. Amit Roy, Mr. Payank Patel and Mr. Fadhel Ben Ettouil, who helped guide me in the technical areas required for my research.

Lastly, I would like to thank all my family and friends who have supported me during this time; I could not have done this without you!

In Memory of

My grandfather, Robert Boara

Without whom, I would likely have never discovered all the opportunities and wonders the city of Montreal holds.

Contribution of Authors

I wish to express my gratitude to those who contributed to the creation of this manuscript-based thesis. The publications integrated into this thesis are of my authorship and co-authorship with my supervisor, Dr. Pantcho Stoyanov. The entirety of the work was completed by me, with Dr. Stoyanov providing guidance in data analysis, result discussions, and overall manuscript organization. Furthermore, credit is due to Ms. Marie-Laurence Cliché, whose research findings inspired a segment of this work. A breakdown of individual contributions is outlined below.

- Chapter 3: Lawrence J., Stoyanov P. A review of tribology in sports with a snowboarding emphasis. ***To be submitted to MDPI Sports***

This section synthesizes existing research on tribology in sports, exploring the potential application of these concepts in snowboard performance evaluations. I acknowledge Rob Lu at Winterstick Snowboards for valuable industry insights gained during our visit to their headquarters. J Lawrence spearheaded the collection and interpretation of prior research discussed in the review, as well as the initial draft. Dr. Stoyanov contributed significantly to the project by refining material focus, outlining experiments, and assisting in manuscript modifications.

- Chapter 4: Lawrence J., Stoyanov P. Tribological evaluation of polymer matrix composites for green alternative replacement in alpine sports: scaling up between laboratory and field testing. ***To be submitted to ISEA Sports Journal***

This chapter centers around a study of a snowboard manufactured with a normal-oriented fiber-reinforced polymer composite base. J Lawrence took the lead in setting up and conducting tribological tests, interpreting results, and providing initial analyses. Dr. Stoyanov played a pivotal role in test designation, helping in result analysis and interpretation. Winterstick handled the manufacturing of the snowboard. Boston Materials provided insightful discussions. The in-field tests, as discussed with J Lawrence, were successfully completed through collaboration between INS and Canada Snowboard.

All authors reviewed the final manuscript and approved of the contents.

Table of Contents

List of Figures x
List of Tables xii
Organization of Thesis xiii
1. Introduction and Motivation 1
1.1. Introduction 2
1.2. Motivation 4
1.3. Objectives 5
2. Literature Review 6
2.1. What is tribology? 7
2.2. Friction 8
2.2.1. Friction of Polymers 9
2.2.2. Friction of Fiber Reinforced Composites 10
2.3. Wear 10
2.3.1. Wear of Polymers 12
2.3.2. Wear of Fiber Reinforced Composites 12
2.4. Lubrication 13
2.4.1. Lubrication of polymers 13
2.4.2. Lubrication of Fiber Reinforced Composites 14
3. A review of tribology in sports with a snowboarding emphasis. 15
3.2. Introduction 17
3.3. Cerebral-Skin Interface 17
3.4. Skin-Garment Interface 19
3.4.1. Garment Design 20
3.5. Human equipment interface/Grip (Garment-Equipment Interface) 20
3.6. Equipment-Environment Interface (Sports Equipment) 21
3.7. Tribology of a Snowboard 23
3.7.1. Mechanism 23
3.7.2. Snow 25
3.7.3. Manufacturing - Materials 26
3.7.4. Manufacturing – Process 28
3.7.5. Manufacturing – structure 29

3.7.6. Waxes 30
3.7.7. Testing Methods 32
3.8. The Proposed Experiment 32
3.9. Conclusion 34
3.10. References 35
4. Development and critical evaluation of polymer matrix composites for green alternative replacement in alpine sports 40
4.1. Abstract 41
4.2. Introduction 42
4.3. Experimental Procedures 43
4.3.1. Material development 43
4.3.1.1. Ultra-high molecular weight polyethylene (UHMWPE) 43
4.3.1.2. Normal Oriented Fiber Reinforced Composite (NOFRC) 44
4.3.1.3. Snowboard Manufacturing 45
4.3.2. Characterization Methods 45
4.3.2.1. Hardness 45
4.3.2.2. Scanning Electron Microscopy (SEM) 45
4.3.2.3. Topography 46
4.3.2.4. Contact Angles 46
4.3.2.5. Snowboard Mechanical Testing 46
4.3.3. Testing Methods 46
4.3.3.1. Category VI – Pin on Disk Testing 46
4.3.3.2. Category V – Static Friction Test 46
4.3.3.3. Category IV – Ice Test 47
4.3.3.4. Category III / Category II – Simulated Snowboard Hill Test 47
4.3.3.5. Category I – Performance Testing Under Relevant Conditions 47
4.4. Results 48
4.4.1. Characterization 48
4.4.1.1. Hardness 48
4.4.1.2. SEM 48
4.4.1.3. Topography 49
4.4.1.4. Contact Angles 49
4.4.1.5. Snowboard Mechanical Testing 50

4.4.2. Testing 50
4.4.2.1. Category VI – Pin on Disk Testing 50
4.4.2.2. Category V – Static Friction Test 51
4.4.2.3. Category IV – Ice Test 52
4.4.2.4. Category III / Category II – Simulated Snowboard Hill Test...............................53
4.4.2.5. Category I – Performance Testing Under Relevant Conditions 53
4.5. Discussion 55
4.6. Conclusions 62
4.7. Future work 62
4.8. References 63
5. Conclusion and Future Work...66
5.1. Conclusion..67
5.2. Future Directions 68
5.3. References 70

List of Figures

Figure 1.1 - Schematic of hypothesized meltwater generation [4] 2
Figure 1.2 - FIS fluorinated wax measuring procedure [13] 3
Figure 1.3 - Water droplets formed on NOFRC snowboard base 5
Figure 2.1 - Practical objectives of tribology [21] 7
Figure 2.2 - Schematic of two-body (A) and three-body (B) abrasive wear [23] 11
Figure 2.3 - Shear wear of polymer [27] 11
Figure 2.4 - Schematic of two bodies separated by a fluid [28] 13
Figure 3.1 - Schematic of tribological interfaces for an athlete in competition 17
Figure 3.2- a) Schematic of friction force and EEG reading and b) ERP reading for linen from 50-360ms[13] 18
Figure 3.3 - Close-up images of a) single yarn structure and b) balanced two-ply yarn tested for thermal energy and warm-cool feeling [19] 19
Figure 3.4 - Coefficient of friction data for grip enhancing agents on steel under differing conditions [21] 21
Figure 3.5 - Mean surface area in contact for each force [8] 22
Figure 3.6 - Schematic representation of BL, ML and EHL contacts [24] 23
Figure 3.7 - Friction as a function of film thickness [27] 25
Figure 3.8 - Snow grain shapes from most abrasive (left) to least (right) [32] 26
Figure 3.9 - 3D view of snowboard sandwich structure [37] 27
Figure 3.10 - Unfinished snowboard before grinding [39] 29
Figure 3.11 - Examples of different structures from grinding [44] 30
Figure 3.12 - Polymer base absorbing wax properties through iron application [32] 31
Figure 3.13 - Categorical evaluation of snowboard friction reflecting increasing representation. 33
Figure 4.1 - Categorical evaluation of snowboard friction reflecting increasing representation 43
Figure 4.2 - Morphological features of UHMWPE [15] 44
Figure 4.3 - Manufactured NOFRC Snowboard 45
Figure 4.4 - a) EDS Analysis of cross-sectional area, SEM images at 100x magnification of b) UHMWPE cross section and c) NOFRC cross section 48
Figure 4.5 - a) Average line roughness values, confocal laser microscopy images of b) UHMWPE surface and c) NOFRC surface 49
Figure 4.6 - Surface Energy Compared with Critical Force Ratio Values 50

Figure 4.7 - Coefficient of friction for UHMWPE and NOFRC prepped with a) no waxes, b) hydrocarbon waxes, and c) fluorinated waxes....51
Figure 4.8 – a) Slope schematic to determine static friction theta and b)Average theta to overcome static friction 52
Figure 4.9 - Average Trial Time for Prototype Boards at Different Temperatures 53
Figure 4.10 - Average 50m Trial Times in Athlete Slope Test....54
Figure 4.11 - Schematic of theorized interface for snowboards [22] 56
Figure 4.12 - Sphere point contact on flat schematic [23]....57
Figure 4.13 - Flow in a lubrication layer near a rough wall and smooth wall (adapted from [24]) 58
Figure 4.14 - Depiction of wax removal from a) UHMWPE and b) NOFRC 59
Figure 4.15 - Schematic of hydration layer and plowing of water lubrication (adapted from [25]) 60
Figure 4.16 - Categorical test correlation for categorical testing 61

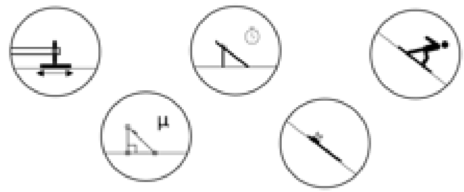
List of Tables

Table 1 - Test snowboard mechanical properties 50
Table 2 – Time trial values for board samples interfacing with HPDE..52
Table 3 – Time trial values for ice interfacing with board 52
Table 4 – Categorical test results summary 55

Organization of Thesis

Chapter 1

- This chapter provides an overview and motivation for the thesis. The objectives of the research are stated.



Chapter 2

- This chapter presents the fundamentals of tribology. The information is differentiated between polymers and composites.

Chapter 3

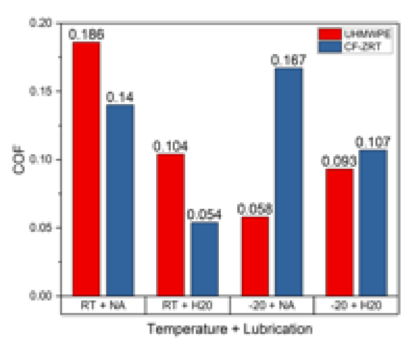
- This chapter presents a collection of knowledge on tribology in sport. It details ways tribology can impact snowboarding.

Chapter 4

- This chapter presents an experiment done to understand how a typical UHMWPE snowboard compares with a NOFRC snowboard through in-lab and field testing.

Chapter 5

- This chapter summarizes the previous two chapters' findings to present the research's major findings and discuss future work.



Chapter

1. Introduction and Motivation

In this chapter…

The motivation and scope and an overview of the area of interest are discussed.

1.1. Introduction

While advancements in performance can be achieved through various avenues, sports equipment exerts a dominant influence owed to its integral connection to the game. An essential equipment performance benchmark lies in its ability to manipulate the environment. In the context of winter sports, this manipulation primarily manifests in the interface between the rider and the snow (see Figure 1.1). The tribological aspects of this system, encompassing friction, wear, and lubrication components, emerge as crucial elements in enhancing the performance of athletes at the pinnacle of their respective sports [1]–[3].

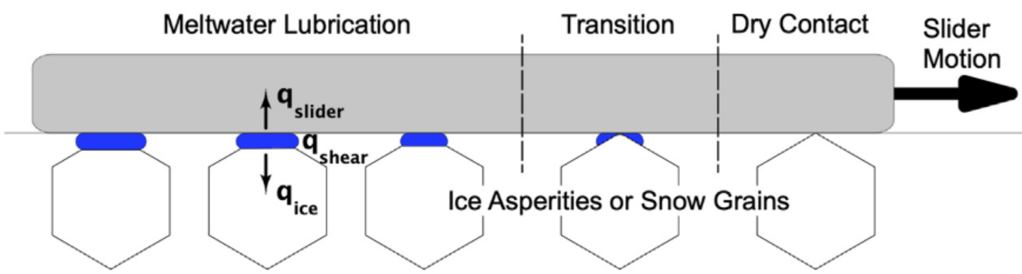


Figure 1.1 - Schematic of hypothesized meltwater generation [4]

A snowboard's main purpose is to keep the rider on top of the snow to avoid plowing, which naturally slows the rider down. While sliding on top of the snow, through a combination of frictional heat, as well as pressure melting, a lubricating film of water forms between the board and the snow [5]. Because the properties of the system can change dynamically due to race conditions, riders are skilled at preparing for all possibilities. One way that riders can mitigate the friction is the preparation of their board with waxes [6]. Up to now, the highest-performing waxes used in the competition were of fluoride composition due to their hydrophobic properties.

A key update in the international snow and ski racing community is the banning of fluoride waxes. Although delayed due to the pandemic and creating methods to verify compliance, it was fully implemented for the 2023-2024 competition season [7]–[9]. The new International Competition Rule (ICR 222.8) states: "Use of fluorinated wax or tuning products containing fluorine is prohibited for all FIS disciplines and levels. Fluorinated wax can be a competitive advantage and its use in competition will result in disqualification" [10]. Because of its current widespread use, the restriction will be a limiting factor on board performance. Figure 1.2 below shows the process to verify the athlete's compliance with the rule change. This limitation has created a need for research into improvements to the snowboard and snow frictional interface [11] [12].

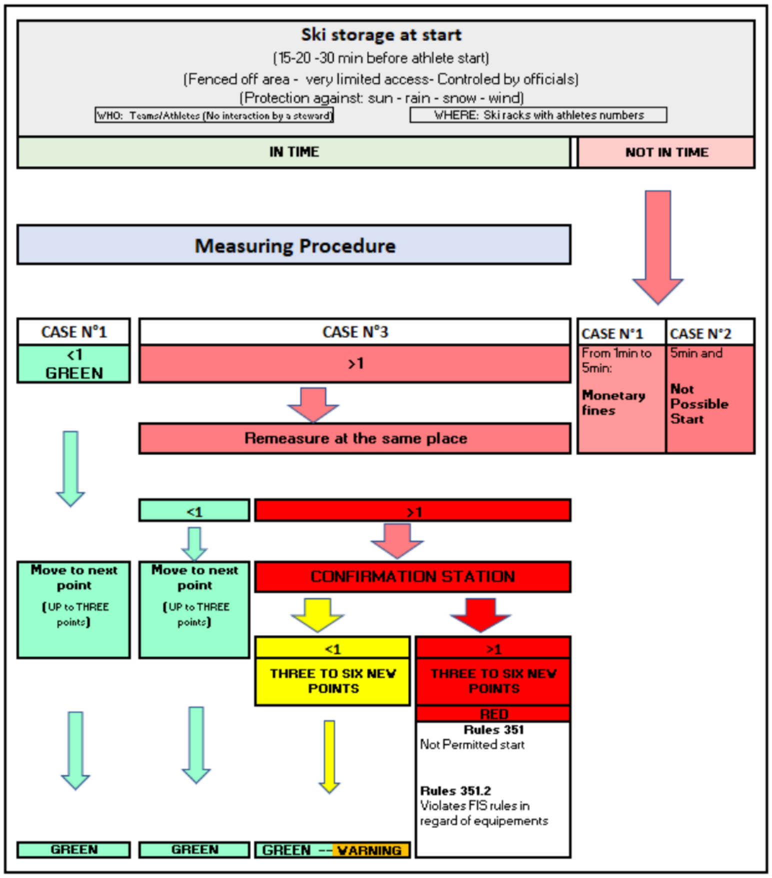


Figure 1.2 - FIS fluorinated wax measuring procedure [13]

The rule change is implicit evidence that the preparation of the board can improve the interface seen by the snow, although detrimental to the environment. Depending on the snow conditions of the day, riders prepare their boards differently. Although mainly passed on as standard methods from rider to rider, there is scientific backing to the technique [14], [15] [6], [16]. The surface modifications will have consequences on the sliding mechanism created by the interfacing surfaces. To optimize friction, the goal can either be to reduce or maximize the coefficient of friction. In this application, the goal is to make the snowboards faster, therefore, to reduce the coefficient of friction, ultimately increasing the acceleration and absolute speed.

Prior findings have indicated that board topology is a large factor in snow friction [17], that snow amounts and properties can impact the coefficient of friction [6], [18]. The focus of this study is investigating the impact of having a base material with higher natural hydrophobic properties [19]. Through this collection of experiments a standard Ultra-high Molecular Weight Polyethylene snow cross board will be compared to a new aerospace grade Normal Oriented Fiber Reinforced Composite board [19]. It has been reported that polyethylene is "hydrophobic (and remains so under humid conditions), hard, highly elastic, can be smoothed and imprinted with different patterns, can be made porous, can easily be coated with binders, does not readily adhere to ice, and its friction is not greatly affected by surface contamination." [20]. The findings discuss the key differences between the materials, how their performance compares across increasingly representative tests, as well as a discussion whether the novel material has a significant impact on the performance of the board.

1.2. Motivation

With the recent advances in normal oriented fiber reinforced composites, the technologies have become even more attractive for ski application [19]. In particular, the ZRT (i.e. Z-axis carbon fiber / polyethylene polymer) and SUPERCOMP materials by Boston Materials have recently been commercialized in ski and snowboard applications due to the improved mechanical properties (such as vibration damping) as well as reduced friction coefficient. However, limited research has been performed on this technology in the sports industry when sliding against snow and ice. Thus, providing innovation in the engineering of new high-performance ski materials and fluorine-free wax solutions will require systematic studies of 1) all steps during the manufacturing processes, 2) the fundamental understanding of interfacial phenomena in sliding contacts (e.g. chemical and physical interactions) among various contact and environmental conditions, 3) the wax application process and 4) the deformation mechanisms and performance of the baseline material.

The main component of this study is to identify next generation fluorine-free ski wax solutions as well as carbon fiber composites sliding against snow to optimize ski performance (i.e. gliding friction and wear) [7]. The general approach for achieving optimal performance with fluorine-free wax and next generation composites will include characterizing of this new base material in sliding applications, and validating this methodology to predict base material in snowboard prototypes. Figure 1.3 below hints at the hydrophobic effect the NOFRC exhibits.

Figure 1.3 - Water droplets formed on NOFRC snowboard base

1.3. Objectives

The main objective of this work is to develop and critically evaluate environmentally friendly alternatives of fluorinated waxes as well as bridging the gap between simplified lab testing and snowboard performance during competition: The following specific objectives are addressed throughout this study:

- **SO1** Development of simplified testing methodologies for the evaluation of ski performance in a lab environment.
- **SO2** Identification and evaluation of environmentally friendly materials for optimal skiing performance. This includes tribological characterization of normal oriented fiber reinforced composite and fluorinated-free waxes under different environments (i.e., temperature, sliding velocity, contact pressure).
- **SO3** Assessment of environmentally friendly strategies in a competition environment.
- **SO4** Provide recommendations on innovative material strategies, wax deposition processes, and critical parameters affecting the tribological performance as a function of environmental and contact conditions.

Chapter

2. Literature Review

In this chapter...

An introduction into tribology is initiated, summarizing the components of friction, lubrication, and wear. Special attention is given to the properties of polymers and composites, highlighting their significance for a deeper comprehension of snowboard applications within the context of this study.

2.1. What is tribology?

Despite being a relatively recent field of study, emerging after the Second World War, tribology has tribal roots, existing informally and understood for centuries, until formal investigation commenced [21]. Originating from the Greek word "tribos," meaning rubbing, tribology encompasses, in simplest terms, three primary components: friction, wear, and lubrication [21], [22]. The optimization of these components within a system depends on the specific application. In certain cases, the objective is to minimize friction and wear, while in others, the goal is to maximize friction. Figure 2.1 below illustrates instances where combinations of wear and friction are strategically employed to achieve success in different scenarios [21] . The examples presented form a compelling illustration that tribology is encountered in nearly every human-made system and occurs naturally within living organisms.

The subsequent sections will underscore the significance of tribology in the context of alpine sports. It is noteworthy that a substantial portion of sliding research is dedicated to higher temperature applications, dominantly in the aerospace and automotive industries. The forthcoming details aim to encompass all facets of tribological effects, with a specific focus on those likely to impact cold temperature environments featuring ice or snow as the counter face.

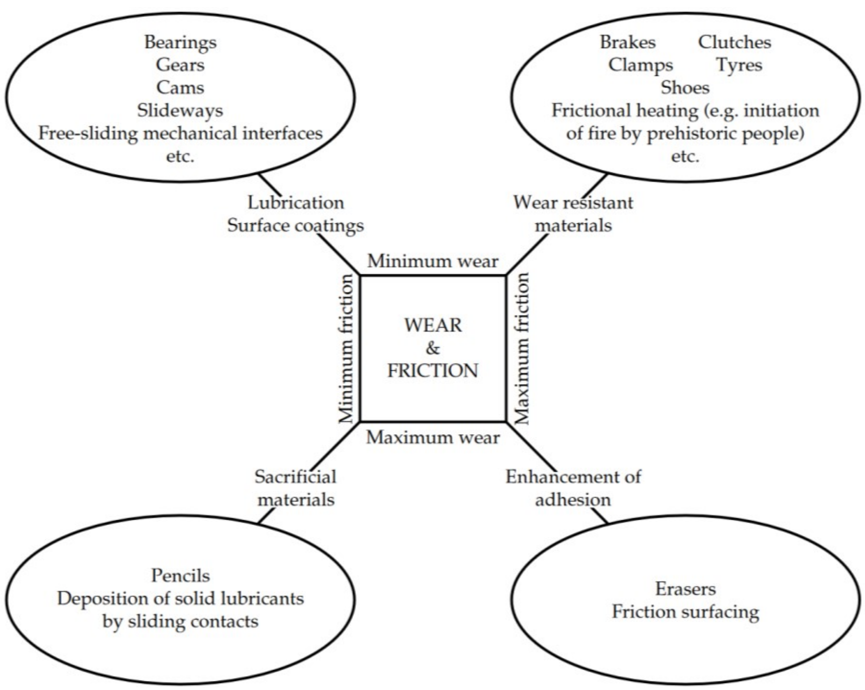


Figure 2.1 - Practical objectives of tribology [21]

2.2. Friction

Friction is described as the resistance to motion. Although it can cause wear, it is commonly referenced when discussing the forces present in the direction opposing motion or intended motion [22]. It is crucial to emphasize that these forces are not inherent to a specific material but rather result from the interaction between two materials. In essence, frictional forces are contingent upon the selection of the two materials under investigation. The coefficient of friction for a given material pair characterizes their tribological relationship and facilitates the calculation of frictional forces. Additionally, a distinction needs to be made between static (μ_s) friction and dynamic (kinetic) (μ_k) friction. The static friction tells of the forces required to start motion, while the later describes the forces needed to sustain motion [23]. Both aspects are of paramount importance for a comprehensive understanding, particularly in applications such as snowboard racing, where both the initiation and continuity of motion significantly contribute to overall performance.

Three laws of frictional mechanics can be seen below [24].

1. Friction is proportional to the normal load.

$$\boldsymbol{F = \mu W} \qquad (1)\ [24]$$

Equation 1 shows that the friction force is a product of the coefficient of friction (μ) and the normal load (W).

2. Friction force is independent of the apparent area between the contacting solids.

Equation 1 illustrates that the friction force is not dependent on the area, merely the force exerted downwards on the surface, and the coefficient of friction between the two materials. In terms of area, two terms are commonly used, apparent area, and real area. The real area is typically much lower than the apparent area, which is the typical engineering area calculated at the interface of the surfaces [23].

3. Friction force (or Coefficient of friction) does not depend on velocity once the motion has started.

As the second law dictated that the area has no influence on the friction force, the third law states the same for the velocities of the surfaces.

Friction is composed of forces caused by deformation (F_d) and adhesion (F_a). The component of adhesion comes from a chemical interaction between the materials, where bonding will occur, creating shearing stresses that will resist motion [2], [24]. Equation 2 shows how the adhesion force is equal to the shearing stress (τ_s) required to create motion times the real area of the junction is A_{r1}. Friction from abrasion can be attributed to the asperities of each surface contacting, deforming, or breaking down to allow the continued motion. Plowing friction is often grouped with deformation as the harder surface wears on the softer. Equation 3 shows the product of σ_y and the real area seen by the formed grooves, A_{r2} [25].

$$\boldsymbol{F_a = \tau_s * A_{r1}} \quad (2)\ [25]$$

$$\boldsymbol{F_d = \sigma_y * A_{r2}} \quad (3)\ [25]$$

$$\boldsymbol{F = F_a + F_d} \quad (4)\ [25]$$

These main modes of forces are combined then to the total friction force, F, as described by equation 4 above.

Since the materials involved with this study are not metals, it is important to make the distinctions for tribology for both polymers and fiber reinforced composites. These details are included below and in the following sections for wear and lubrication.

2.2.1. Friction of Polymers

Instead of deforming in an elastic-plastic manner, the viscoelastic nature of polymers changes their tribological characteristics. As mentioned above in equation 4, the adhesive and deformation sources of friction remain in polymer. A large difference is that they are much more likely to experience elastic deformation. This means that the deformation forces can be much higher. Depending on the contact mechanism, topology and other mechanical properties of the board, these forces can vary [25].

When undergoing plastic deformation, the following equation 5 can be used to predict the coefficient of friction for polymers. p is the flow pressure of the polymer.

$$\boldsymbol{\mu = \frac{\tau_s}{p}} \quad (5)\ [25]$$

When elastic deformation is present, the coefficient equation changes to that of equation 6.

$$\mu = K * \frac{\tau_s}{E^x} * W^{x-1}$$ (6) [25]

Additionally, the angle of deformation in asperities can be calculated using equation 7.

$$tan\theta_{lim} = K\frac{H}{E}(1 - v^2)$$ (7) [25]

Equations 5, 6 and 7 emphasize how the mechanical properties of the polymer, such as Young's Modulus (E), surface parameters (K,x), indentation hardness (H), Poisson's ratio (v), and plastic flow constant (k).

2.2.2. Friction of Fiber Reinforced Composites

Composites themselves introduce both positive and negative implications for tribology. Since they are composed of multiple materials, there is balance in the properties of each. Since one benefit of imbedding fibers in a polymer matrix is to add rigidity, it also creates more stiffness at the interface, making a high surface temperature. However, the polymer material can help with lubrication of the system. Again, we find that there are many factors, such as selection of fiber, matrix, and geometry, that can alter the performance [23], [25].

2.3. Wear

Wear is the material damaging or surface altering of a surface in contact with another. Wearing surfaces will lose material form either mechanical or chemical means, and can occur through multiple mechanisms depending on the relative motion and characteristics of the materials and the lubrication present [22]. Although material wear is typically not sought after due to the cost, there are situations where wear is desired. A pencil and chalk are simple examples that rely on wear to function [22]. In the same way friction has multiple sources (i.e., adhesion, abrasion, ploughing), wear has multiple mechanisms. Typical types of wear can be adhesion, abrasion, surface fatigue, corrosion, fretting, impact, erosion [23], [26].

Main modes of wear with a concise description are below [23].

(1) Abrasion – abrasion occurs when two surfaces of different hardness, as the material of the softer material is plowed by the harder material. This can happen with two or three bodies present (See Figure 2.2).

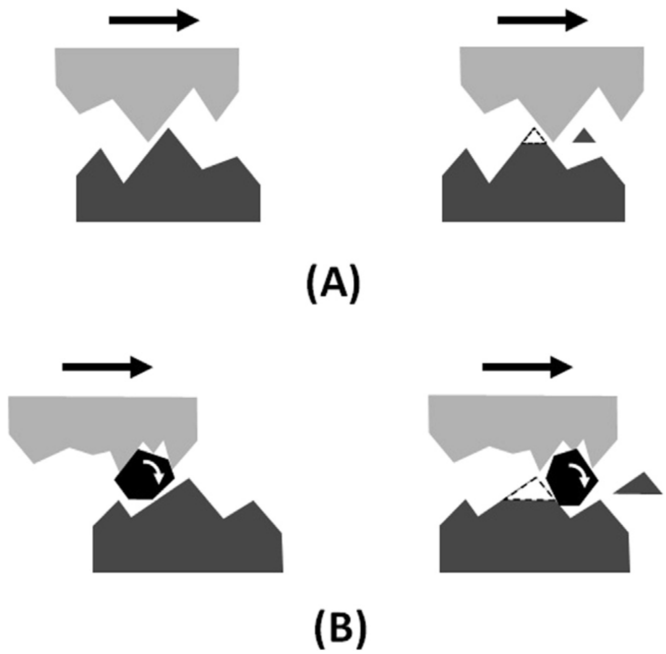


Figure 2.2 - Schematic of two-body (A) and three-body (B) abrasive wear [23]

(2) Adhesion – adhesion is very coming with interacting surfaces. Described as “cold welding” sometimes, fragments of one material come off on the other material. Figure 2.3 depicts shearing wear of a polymer.

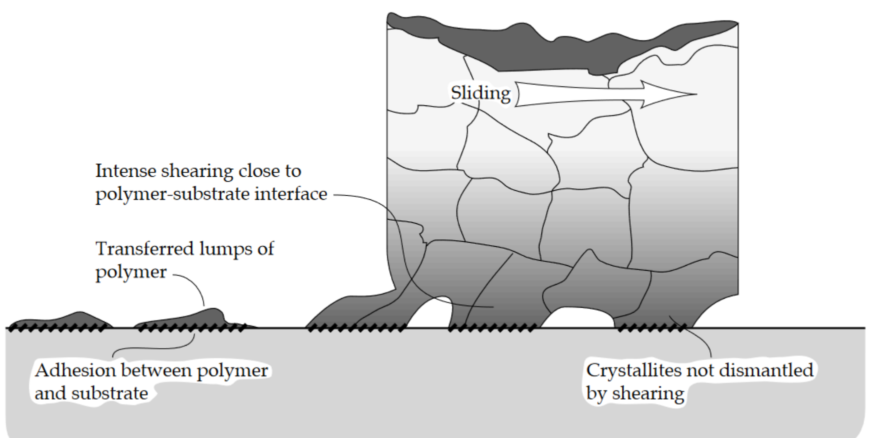


Figure 2.3 - Shear wear of polymer [27]

(3) Surface Fatigue – similar with other engineering applications, the cyclic loading of a material will lead to surface decay.

(4) Corrosion – corrosion is mainly the degradation of material from chemical interactions that will spur other forms of wear.
(5) Fretting – fretting is considered a special form of wear, comprised of a combination of adhesion and abrasion, where the vibration causes the asperities to collide in different ways.
(6) Impact – another hybrid mechanism of wear, impact wear comes from repeated impacts from another body.

2.3.1. Wear of Polymers

Although there is a lot of research done in the wear of metals, the focus of this project will be the main wear mechanisms in non-metals, specifically polymers. However different, they still rely on mechanical, thermal, and chemical processes [2]. Much of the information on polymer wear on low temperature applications is limited.

Polymer wear can be focused mainly on abrasive and fatigue wear as well as roll formation. The abrasion, similar to the metal wear, comes from the harder material cutting into the polymer, removing material from the surface [2]. It can be imagined that this type of wear might occur at very low temperatures, with a larger presence of ice, or when hard pollutants are found within the snow due to grooming or environmental conditions [6]. Fatigue wear would happen in similar instances, however instead of slicing into the softer surface, the contact will cause cyclic deformation, slowly altering the surface of the snowboard. Additionally, since the counter face is comprised of water in ice or snow form, the instances the board will wear before the snow are minimal, but not negligible.

The polymer will also go through a running-in phase, not unlike some metals [25]. This can also be described in snowboarding as the time that it takes to break a board in, which would be the steady-state, or longest duration of similar board properties.

2.3.2. Wear of Fiber Reinforced Composites

Wear of FRPC will lead to failures in the composite through one of the common mechanisms. These mechanisms are fiber fracture, matrix cracking, and delamination. Since most snowboards are made using polymers, these failures are not common in the sport. However, it could be predicted that some combination of these might occur over time with usage of a composite board [25].

Although research has indicated that the orientation of the fibers can affect wear, it does not state how the wear is impacted with fibers with length perpendicular to the sliding direction as will be done with the composite test board. These boards are technically manufactured as cross laminate, meaning that they should have the lowest wear rate if the fibers easily detach from the board [25]. These fibers could potentially act as the hairs that are scraped off polymer boards over time.

2.4. Lubrication

The last component is lubrication, which has the primary use for minimizing friction and controlling wear to increase the efficiency of the system and the lifetime of the materials. Although most lubrication is liquid based, lubrication can be any substance that alters the tribological interaction of the two surfaces, including solids and gases [22]. Lubrication can either exist in the system initially or be added or created during motion, without the presence of lubrication, the system is at risk of wear and higher friction, causing failure or requiring repairs and replacements for one or both interfacing surfaces. Figure 2.4 below illustrates the forces that can occur between two bodies separated by lubrication.

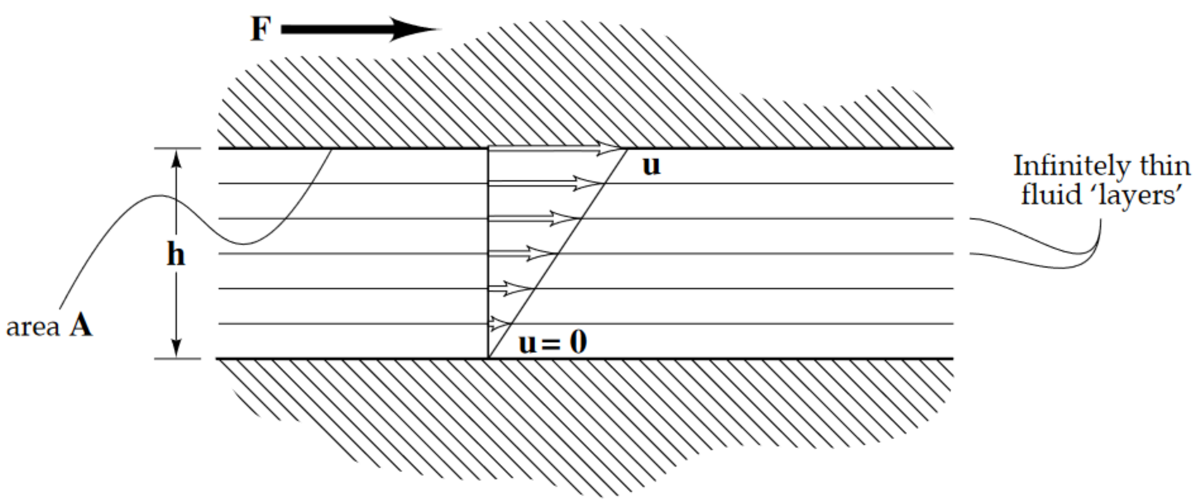


Figure 2.4 - Schematic of two bodies separated by a fluid [28]

2.4.1. Lubrication of polymers

In the same manner as metals, lubrication can reduce friction and wear with thermoplastics, notably, the adhesion. The mechanisms that can be credited are the following [25]:

- Absorption on the contact surface

- Chemically modifying the surface
- Separating the surfaces

Embedding material in the surface and chemically modifying the surface can impact the bonds that are made with the material. Some materials might not react well to certain lubrications. For example, nylon is degraded after long exposure to moisture (i.e., water). This specifically would be a bad choice for snowboard material selection. Since the main mode of lubrication will be meltwater, we will see this discussed later. Chemical lubrication can be seen by DPS in their phantom wax coating [29]. The most valuable takeaway for snowboarding application is that polymers can absorb lubricants which can modify the mechanical properties.

2.4.2. Lubrication of Fiber Reinforced Composites

As the combination of fibers and matrix creates a mix of properties that can occasionally clash, has the potential to positively affect the system. Through the design of the material, the components can aid in the lubrication need from the fibers or the matrix. The fibers, such as graphite, can be added to wear away, allowing the material slide smoother. Alternatively, a strategic matrix can be ideal in creating a transfer layer, reducing the wear and friction as well. As FRPC tend to get stiffer with the addition of fibers, these are necessary consideration when choosing the proper material for application [25].

Chapter

3. A review of tribology in sports with a snowboarding emphasis.

In this chapter…

A comprehensive review of tribology in sports is presented. Prior findings show how different levels of interfaces can impact athletes. Furthermore, this review undertakes an in-depth exploration to comprehend pertinent information in the realm of snowboarding tribology.

3.1. Abstract

This review extensively explores the tribological interfaces experienced by athletes, spanning from the innermost to the outermost levels. Previous research findings are systematically categorized into four distinct levels: 1. Cerebral-skin, 2. Skin-garment, 3. Garment-equipment, and 4. Equipment-environment. The cerebral-skin level examines the friction of touch and its correlation to perceived variations in friction values. Building upon this, the skin-garment level delves into garment-specific considerations, focusing on how individuals perceive material characteristics. The Garment-equipment level extends the exploration, detailing the impact of an intermediate layer on performance and perception. Finally, the equipment-environment interface elucidates how equipment can manipulate the surroundings differently. Key factors are identified through a systematic analysis of these categories for athletes and equipment, contributing to multiple facets of overall performance. Scrutinizing each level yields valuable insights for experimental design, offering ways to enhance interfacing surfaces at both micro and macro levels of the athlete's experience.

Concluding this review is a proposed investigation outline, targeting the tribological impact of altering base materials in a snowboard. This exploration aims to address the challenge posed by the prohibition of fluorinated waxes in professional competition, seeking alternative solutions for optimal performance.

3.2. Introduction

Simply stated, tribology is the study of surfaces rubbing together. It consists of interfacing surfaces' friction, wear, and lubrication. Although tribology has been expanding its vast impact in aerospace and automotive industries research [1], it has also expanded to biomedical, biomechanical applications [2]–[4], apparel [5], and sporting goods [6]–[11]. The discussion expands outwardly encompassing impacts on the brain due to surface differences concluding with the interaction between equipment and the environment. Figure 3.1 below shows an athlete, labeling the different levels of tribology impacting performance.

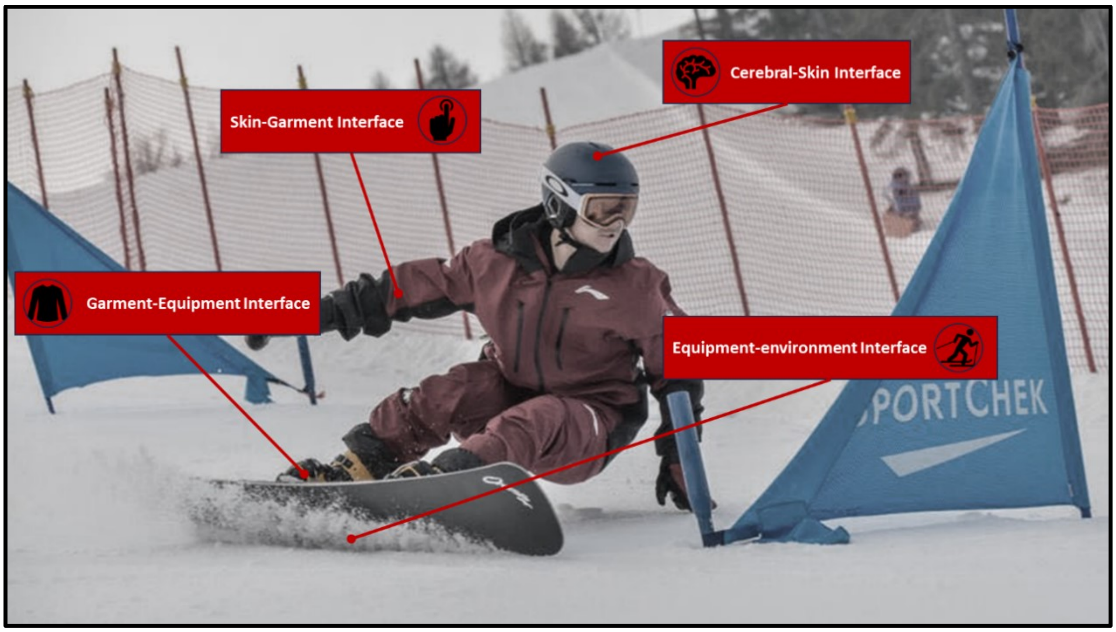


Figure 3.1 - Schematic of tribological interfaces for an athlete in competition

3.3. Cerebral-Skin Interface

The human skin is the most external interface for contact, giving feedback to the brain upon product contact with the skin. Therefore, understanding the skin's interaction with different surfaces will identify key areas of focus when designing. A mobile skin tribometer was created by Temel et. al. to evaluate coefficients of friction consistently and accurately between the skin and other materials. Variables that can be modified are normal load, velocity, and motor speed. Having more tools that can be used on-site and with adjustable inputs allows for testing to be done outside of a lab [12]. Before the mobile testing device, research was conducted by Derler et al. comparing friction values between the skin and multiple materials, then furthering the investigation to determine that the most promising mechanical skin equivalent in dry conditions is a polyurethane-coated polymer fleece [2].

Although a coefficient of friction is a descriptive value of the interface, it doesn't describe what the person feels during the interaction. Fang et al. investigated the relationship between neurophysiology, subjective perception, and skin friction using a friction-EEG (electroencephalograph) bed and ERP (Event-related potentials) readings on samples of Linen, cotton, polyester, and silk. The findings show that in the skin-fabric interface, adhesive friction is dominant. The stickiness perception was mainly dominated by the surface roughness of the fabric as well as the water absorption capacity of the material. This stickiness perception is reflected in the ERP images specifically in the parietal and occipital lobe [13]. Figure 3.2a) shows the coefficient of friction with EEG force seen consequently. Figure 3.2b) shows the ERP results for 50-360ms when in contact with the linen sample. Different distinct regions are shown for other fabrics.

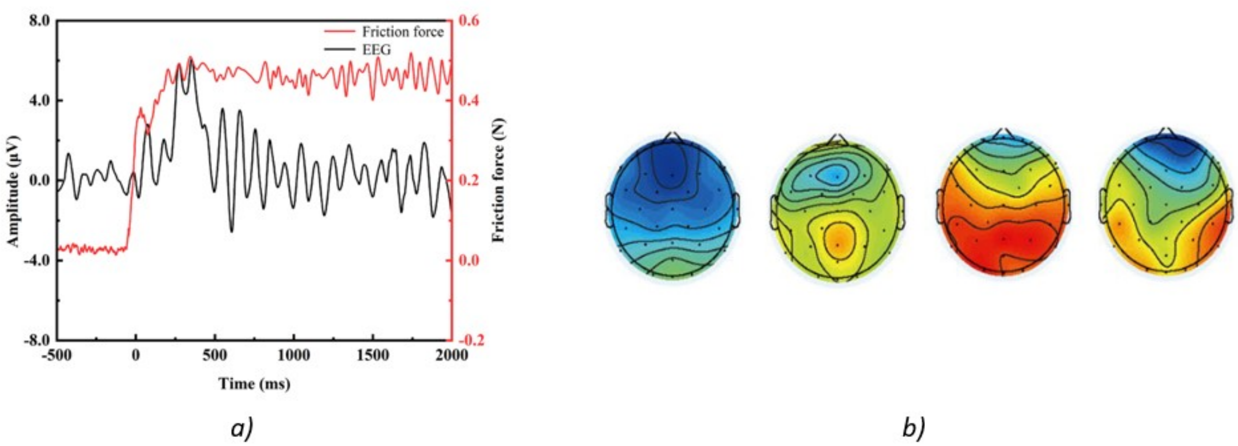


Figure 3.2- a) Schematic of friction force and EEG reading and b) ERP reading for linen from 50-360ms[13]

The different characteristics of materials have a distinct impact on how they are perceived by the user. However, since the goal of this review is to outline key findings in tribology for sport, this neuro level of perception will not be discussed further. More than touch, other senses that are beginning to quantify the effect it has on the chemical reaction by humans are oral tribology and acoustic tribology. These areas of study look at the tribological characteristics of food or edible substances, and the different sounds created by materials with changing surfaces [14], [15] For this review, the key insight is the perceptual differences in fabric feels based on tribological factors will be touched on relating to the performance of the garment.

3.4. Skin-Garment Interface

In a review of factors between skin and different textiles, D'Souza et al. looked into the categories of skin friction, explaining that key variables to consider are anatomical region, humidity, counter material, and fabric type, concluding that these issues should be addressed before they become issues in the product, that can be validated with tactile perception testing to verify low enough friction values [16].

Before this review, Darden and Schwartz examined the effect of skin tribology on tactile attributes of polymer fabrics [17]. They aimed to narrow down perceptions of different polymers using Quantitative Descriptive Analysis (QDA). Having subjects touch materials, and calculating a friction value, they asked for feedback on slipperiness, fuzziness, abrasiveness, and sensible texture scores. In summary, although differences were evident between the materials, there was no major correlation between the four scores and friction values.

In their exploration of "affective engineering," characterized by the inclusion of subjective comments for human factor considerations and scoring, Barnes et al. investigated the perceived differences in glass with varying surface finishes. Relative to the roughness of a fingertip, counter faces with lower roughness are perceived better than higher roughness [18].

With a slightly different approach, Pac et al. compared the thermal sensation of materials. The materials selected were two types of cotton, two types of yarn (shown in Figure 3.3), and three types of jersey material. Key distinctions between thermal sensations are suggested to be from air present in the fabric type utilizing convection heat transfer. In this way, hair or rougher surfaces are typically perceived as warmer, likely due to the air that gets trapped on the surface by asperities [19].

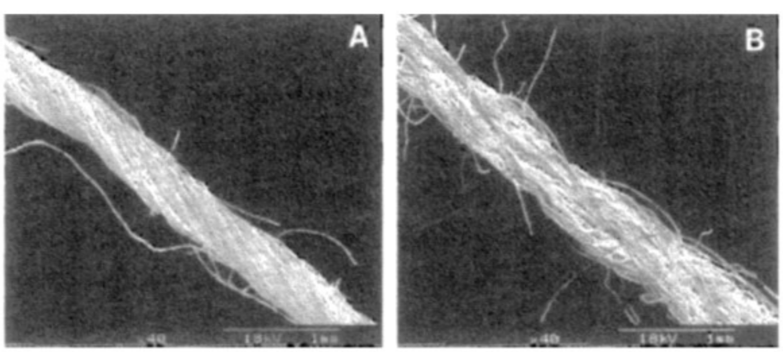


Figure 3.3 - Close-up images of a) single yarn structure and b) balanced two-ply yarn tested for thermal energy and warm-cool feeling [19]

Finally, in the context of evaluating other contacts that may occur on the skin during sports played on turf, a comprehensive assessment becomes imperative. Recognizing the ethical constraints of conducting tests with real participants, Tay et al. discussed the importance of accurate substitutes to represent skin-turf friction. The authors emphasized that achieving a more precise representation involves using materials capable of generating a lubrication layer, a characteristic not achievable with steel substitutes. [20].

3.4.1. Garment Design

The above studies highlight the importance to work into the development of garments. With the popularity of compression fits in apparel, the sensation of negative fitting clothing was investigated by Troynikov et al. Findings discuss that tension in the material will increases friction seen between the skin and the garment as well as the wetting of the material, the later finding being of higher magnitude [5]. When comparing perceptions of products, tactile feedback from the surface of clothing influences the participants' opinions. Novel research is undergoing on the perception of acoustic feedback created between the garment and the skin/nails. With tremendous amounts of contact areas of subtle influence are being researched deeper for better perceptional performance [15]

3.5. Human equipment interface/Grip (Garment-Equipment Interface)

Examples of the next level of interface include the relationship between hockey gloves and the stick, as well as the interaction between socks and shoes. A study by Lewis et al. investigated a some cases studies of friction created by hands and other objects [21]. In the instance of rugby balls different pimple sizing on the ball were compared. The large pimples were better in dry friction and had reduced friction in wet conditions, while the smaller pimples showed less friction dry, but maintained through the wet conditions. Lubrication is a key ingredient in the frictional performance of some materials. With regards to grip enhancers used by weightlifters and rock climbers, it was determined that most were not beneficial until the finger or the surface was wet. Figure 3.4 below highlights conditions that varied performance of grip enhancers [21].

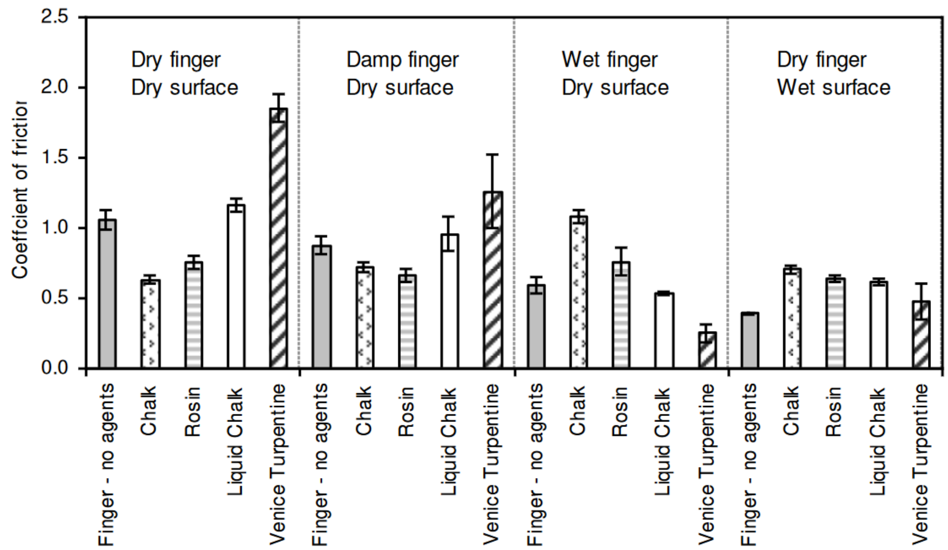


Figure 3.4 - Coefficient of friction data for grip enhancing agents on steel under differing conditions [21]

To improve the grip exhibited by the hand on a frisbee, a glove was added. Although the friction values were increased, the material between the hands reduced the feel which is the suggested reasoning for reduction in accuracy of the tester [3].

3.6. Equipment-Environment Interface (Sports Equipment)

The following studies discuss the impact of changing tribological performance of equipment in sports that directly interfaces with the environment.

Anderson discusses in a journal how the spin imposed by the golf clubs from it's design is a large factor in how much carry the ball gets. By altering the amount of spin created by the interaction between the face of the club and the ball, it can cause the ball to go longer or shorter distances depending on the need of the golfer. This is why golfers have an entire bag dedicated to different clubs [6]. Specifically, Zirconium based golf club heads were found to have varying amounts of wear depending on the counter ball material [10].

Marinkovic et. al investigated the relationship between shoes and floor in ball-room dancing through principals of conservation of energy [22]. With energy loss due to the translational and rotational forces compared through different flooring, gender, and dance tempo show that different tempo dances can be impact. A second finding of this research is how floor-shoe interface can greatly impact injury likelihood.

In the world of tennis, Barry and Milburn collected factors that influence the friction seen between a shoe and the surface below it. Although they mention that the friction cannot be perfectly predicted by the properties of the shoe and surface, research has been continued with the goal of calculating the forces in different systems by other entities [23]. Clarke et. al experimented with acrylic courts of different hardness and the relationship between flat (4S Flat) and herringbone (Barricade 6.0) outsole. They discovered that as the normal force increased, an outsole with lower roughness had a larger increase in surface engaging area (A_0) of contact. Figure 3.5 below illustrates the finding that increasing roughness had a negative impact on the surface engaging area during the test [8].

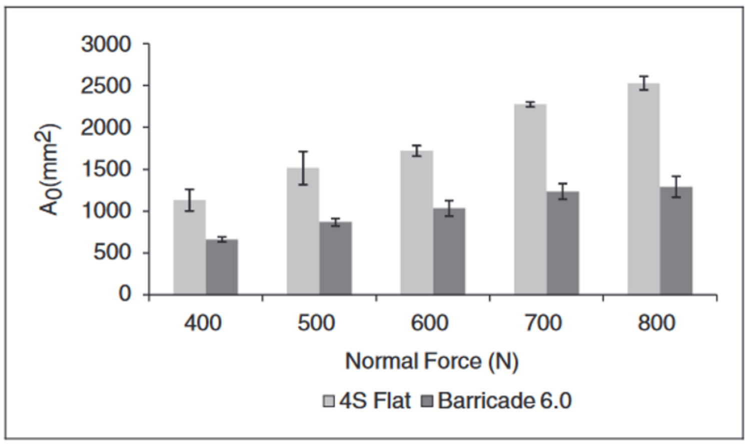


Figure 3.5 - Mean surface area in contact for each force [8]

Aubert et al. reviewed the instances of friction force instances in a bicycle transmission. They were determined to be in a lubrication regime outlined in figure 3.6 below between boundary lubrication, mixed lubrication, and elasto-hydrodynamic lubrication. Through testing with rigs, it was determined that the closer the representation to real world, the higher the variability [24]

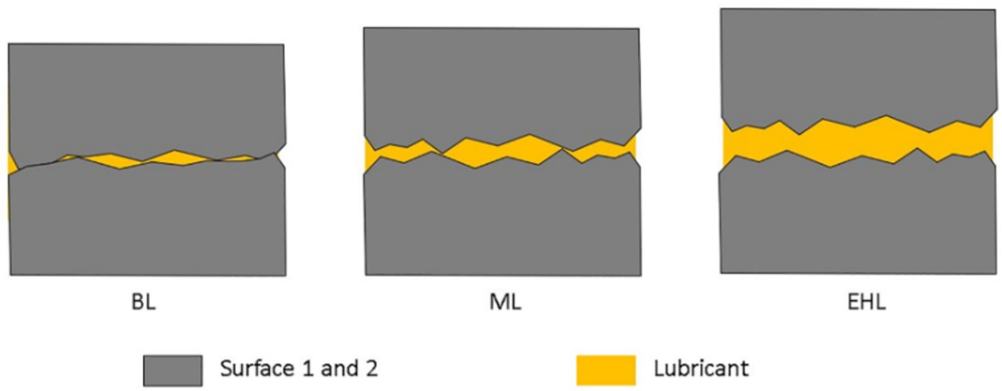


Figure 3.6 - Schematic representation of BL (Boundary Lubrication), ML (Mixed lubrication) and EHL (Elasto-hydrodynamic lubrication) contacts [24]

Another study by Varenberg et al investigated the frictional analysis of rubbers for table tennis. The interface between the paddle and the ball can influence the power and spin placed on the ball. They propose that “friction” can be described as a ratio of the slope of the friction force divided by the normal force, which can be compared to look at the “stickiness” of each rubber [7].

Hjelle et al. looks at the frictional interface between speed skates and ice, ultimately finding that a significant increase in temperature will increase the coefficient of friction, further suggesting there is an optimal temperature for performance [9].

The studies in this section illustrate the need for tribological understanding for sports. The material in the next section will discuss the understanding of tribological factors in snowboarding.

3.7. Tribology of a Snowboard

Considering the broad range of areas that have been discussed above, it is apparent that investigating the snowboarding system with a tribological approach is necessary to improve the current state. Some research has been conducted generating findings that will aide developing the direction for further studies in this category.

3.7.1. Mechanism

Although it appears that the snowboard slides down the hill on top of the snow, this does not intuitively explain the phenomena that is occurring underneath the base of the board. Some studies discussed in this section touch on the tribo-system of snowboarding.

The earliest studies on mechanisms for sliding on ice were conducted by Bowden et al (1939) [25]. The results showed that thermal changes that occurred during sliding were important to reduce friction. Moreover, the water film that was produced at the point of contact was necessary for motion, and pressure melting was correlated to temperatures closer to 0°C [25]. A decade later, he published a second paper discussing the friction of snow and ice. These results discussed how hydrophobic properties can be useful around 0°C, and that friction heating can create a lower kinetic friction force through local melting [26]. Colbeck looked into kinetics of sliding along snow and noted that with regards to the layer that is generated from factors such as speed, grain size, and temperature, has an optimal thickness when the aim is to minimize friction [27]. Figure 3.7 shows the relationship between friction and lubrication film thickness. Reviewing again in 1988, he suggested that the roughness of materials tells of the actual contact areas, precisely, what area is in solid-solid sliding, and what area is lubricated. The friction seen depending on film thickness can be understood better with more material properties collected [28]. More recently, a group of researchers have had significant findings in the field since 2016 is the authors of Gliding – Team Snowstorm [29]. Multiple areas of snowboard development and environment are vital to understanding the whole tribology picture. An estimation that in cross country skiing, a 51km race time can be reduced by 1.5 minutes following a .001 reduction in coefficient of friction spotlights the long term effects of energy saving in alpine sports [30]. Testing small steel samples against compacted snow revealed that contrary to general understanding, there is no water layer produced likely due to the samples loads and thermal properties as they were sliding against the snow [31].

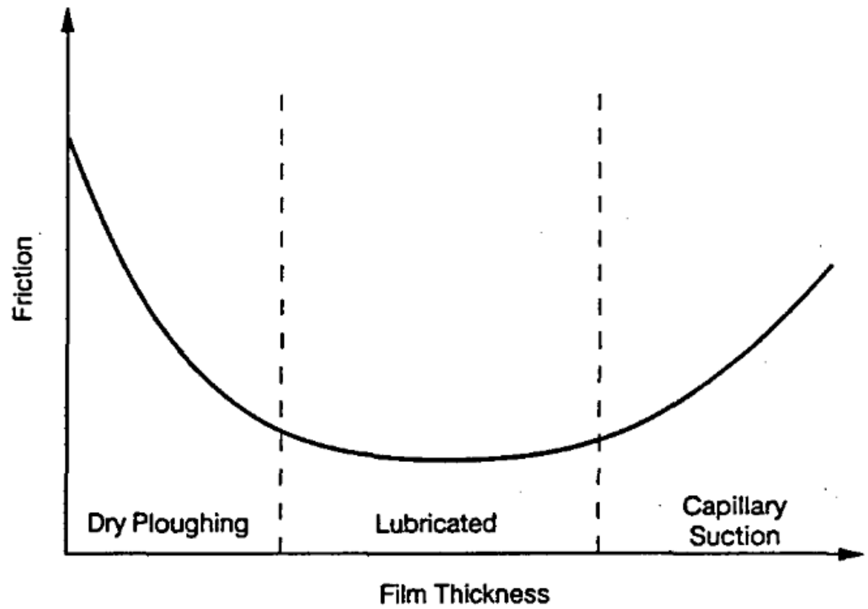


Figure 3.7 - Friction as a function of film thickness [27]

3.7.2. Snow

Commencing from the ground, the initial factor encountered is the snow. Based on temperature, humidity, weather conditions and snow care, among other factors can change the nature of the snow. For these reasons, understanding the dynamic nature is vital to being able to manipulate the frictional forces and wearing seen in the system. At the surface level, cold and new snow, will be harder, and more likely to wear against the board, while warmer and old snow has the opposite effect. Figure 3.8 shows how these conditions as well as the shape of the grain can be impactful [32]. The geometric properties of the snow grains can be seen in the figure below. The grains on the left represent the colder, harder, with the ability to penetrate to the board base and wear. Conversely, moving left to the right, the grains transition to the warmer, soft snow that cannot penetrate like the newer snow.

Figure 3.8 - Snow grain shapes from most abrasive (left) to least (right) [32]

Wolfsperger et al. (2021) looked into how friction can be predicted by the physical snow quantities, they developed a statistical model estimating the likely coefficient of friction due to the snow parameters [33]. Lever et al. (2017) looked closer at the snow grains to gather insight on how the micro interactions were influencing the interfacial forces. Using a tribometer and compacted snow the pressure applied as well as slider speed and air temperature were varied. Although contradictory, their discovery of minimal surface melting suggests the mechanism is not representative at micro scale as in real applications [34] A track created with acoustic sensors and microphones and accelerometers in the snow close to the surface showed that optimal pressure distribution when sliding is important for cross country ski performance [35]

3.7.3. Manufacturing - Materials

First snowboards were made of wood and have evolved to use materials with better properties for performance. The boards are built in a composite sandwich fashion (Figure 3.9) which allows for multiple layers, creating dynamic characteristics throughout the board. Each layer, from the top down, has the following purpose [36], [37].

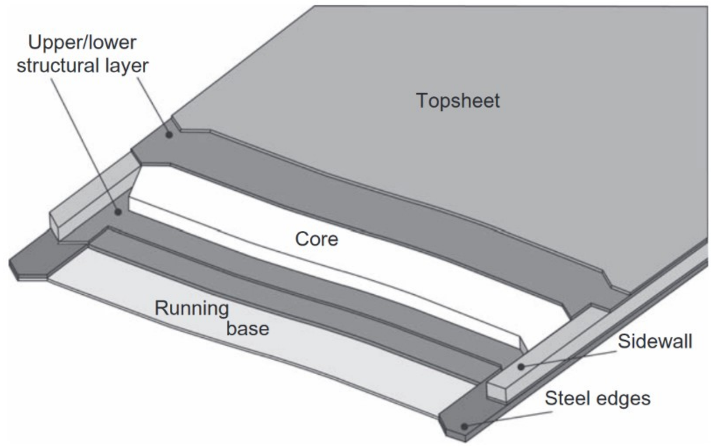


Figure 3.9 - 3D view of snowboard sandwich structure [37]

- Topsheet: This layer is seen when viewing a board on the side of the binding attachments. It is designed to protect the other layers from the external elements and can also be an aesthetically designed sheet for graphics.
- Structural Layers: The upper and lower structural layers are designed to support the entire structure. They are typical made of a composite material. These sheets are done through a layup process, which can change configurations based on the purpose of the board.
- Core: The core makes up the bulk of the weight of the board, and as the name implies, contributes the main properties of the board. It is typically constructed from gluing strips of wood together in the longitudinal direction. The glue between the strips has a small width and therefore acts like tiny beams, supporting the structure when bending in the same direction. The width of each strip as well as the stiffness can create a dynamic profile of performance across the board [36], [37].
- Sidewalls: These are placed around the perimeter to support the core and assist with the sandwich structure. The steel edges are also added around the base to be the protective outer layer, and add a surface that can be tuned to grip the ice during use.
- Base: The running base is the material designated to connect the board with the snow underneath. This material is typically made of Ultra high molecular weight polyethylene. Frictional effects are a resultant of what material is used on the base of the board.

The board's performance is naturally linked to the make-up materials. One study investigated the influence of stiffness changes due to temperature drop and found that the main elements remain the same until -17°C accompanied with increase in stiffness [38]. The importance of understanding these effects when designing is vital for the board to perform as intended.

3.7.4. Manufacturing – Process

The different layers mentioned above need to be bound together to function the intended way. The process is as follows [36].

1. Core creation – the base is created by gluing strips of different wood types together, creating a spectrum of stiffnesses from the midline to the edges.
2. Base addition – the wood core is then glued to the base material. This material combination is then CNC cut to shape.
3. Structural layers – once the proper shape is set, the steel edge is set along with the addition of structural layers. These layers can be added in different orientations to optimize the mechanical properties of the board. The materials are then prepped with a 2-part epoxy for bonding.
4. Heat Press – The board is then placed in a heat press with template shapes to form and bond the layers together in the desired camber. Once the board has been properly cured, it is removed from the mold. Figure 3.10 below contains an image of the NOFRC base snowboard prior to grinding and trimming.
5. Grinding – The unfinished board is then trimmed of any debris before have the base grinded into a standard finish. Additionally, for specialized racers, a requested structure can be imposed on the board to improve the performance for race conditions.

Figure 3.10 - Unfinished snowboard before grinding [39]

3.7.5. Manufacturing – structure

With a newly pressed board, the base material comes out raw, with excess material and a base not ready for riding on. To get the board slope ready, it needs to be polished and set with a “structure”. Structure refers to the final surface conditions imposed on the board before racing. The polishing is done with a belt grinder progressing from course to the finest. Once the board is polished, the board will be passed through a stone grinder to add a structure. Depending on the anticipated race conditions for racers, different structures can be added to the board for minimal friction. Figure 3.11 shows different standard structures for reference.

As discussed in the mechanism used to slide, optimal structures will depend on the snow conditions. For dry conditions, a structure that helps create a water layer is ideal, while in wet conditions, repelling the water layer is the desired effect of the board. Generally, for wet conditions, large structures are made to wick away the water. Dry conditions utilize a thin structure to keep the water under the board. These structure patterns can change the surface area, which will largely impact the actual friction seen by the board. The formula for frictional force gives insight into how the surface area can greatly impact the forces seen.

The structure describes the topology of the finished board. Lungevics et al. (2021) review of topography analysis. They created a few samples with different roughness values, and showed how the coefficient of friction can vary with different velocities [31]. Multiple studies have shown an increase in friction with sliding speed. Different structures have minor changes to the coefficient of friction, increasing slightly with reductions in roughness [40].Scherge et al., (2021) found that the topography of the actual contact area are a large factor in design for performance [41]. The roughness not only impacts the area seen by the interfacing surfaces, but the way water bonds to the surface – hydrophobicity. By testing materials with different "smoothness" it was found that lower roughness was better when mitigating static friction, however when dealing with wet conditions, a more hydrophobic surface will glide better [42]. UHMWPE, discussed as the most common material for snowboards, was looked at with different surface features sizes. As the size decreased, the contact angle increased, showing that the changes that can be imposed on the material can also be tuned to hydrophobic needs of the interface [43].

In summary, the structure of the board is very important to mitigate issues when dealing with manipulating the snow, however the dynamic properties of snow still make it difficult to create a solution with modifications to the surface shape.

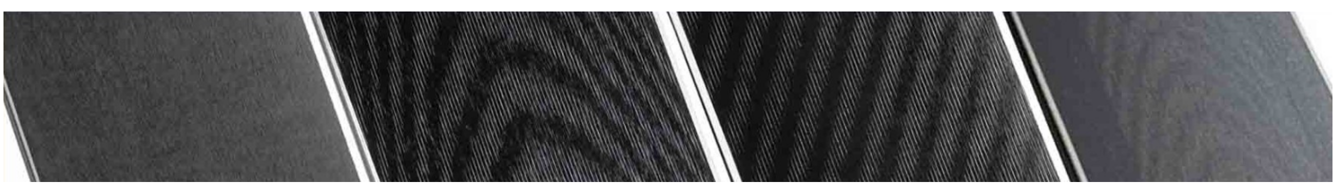


Figure 3.11 - Examples of different structures from grinding [44]

3.7.6. Waxes

Once a structure is added to the board, waxing is the main surface treatment for boards that can reduce frictional forces during racing. Although not conducted through surface treatment means like aerospace, there is a standardized process in the snowboarding world, accepted by most athletes. For recreational snowboards a general hydrocarbon wax is applied that is meant to last for a whole season [45].

For racers, the waxing procedure is tuned and precise. It is very important to schedule and thoroughly wax the board. Although methods vary slightly from person to person, the end goal remains the same – get the board to absorb the material properties of the wax. This is done by applying the wax to the board, then moving over it with a hot iron, to open the pores of the board and allow the hot wax to enter the structure. Once the wax has cooled, it will be scraped off. Micro hairs being present on the board have been discussed, and the scraping process removes them as well as the excess wax. The board is then brushed to remove the debris and remove wax the scraper could not. This process is repeated multiple times to get the most wax properties into the board and remove the most amount of the hairs [32], [45]. Although wax layer on the surface might be seem helpful, it is more important to bond the wax to the board base than to have a significant amount present on top [46]. The ideal deposition results in wax imbedded in the board as figure 3.12 shows.

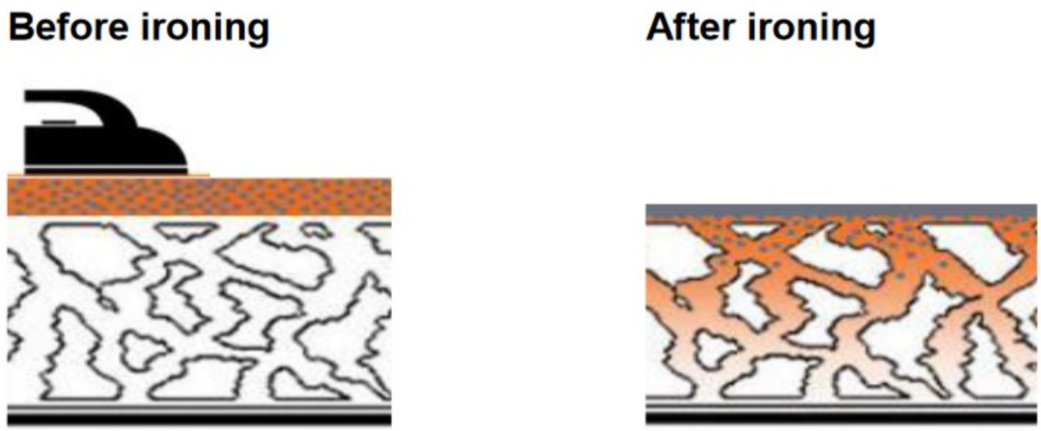


Figure 3.12 - Polymer base absorbing wax properties through iron application [32]

Depending on racing conditions, different waxes are used for performance enhancement. Hydrocarbon waxes are the most basic unit, and the base for most waxes. They represent the deck of cards sliding off one another analogy lubrication being soft naturally. When conditions are very dry, static friction becomes an issue without much water formed for a lubrication layer, and molybdenum additives are utilized to reduce the electro-static friction. Molybdenum's similarity to graphite especially dealing in with lower temperatures are likely what allow it to handle debris from the slopes [47] readily.

Lastly, to reduce the suction in wet conditions, waxes with fluorine additives are best due to the hydrophobic properties [32], [45]. Moore discusses the benefits of Teflon also known as Polytetrafluoroethylene (PTFE), which as a hard plastic, behaves similar to molybdenum disulphide. The waxing done to boards prior to racing can considerably have the similar effect in increasing the contact angle for hydrophobicity of UHMWPE that the PTFE material would otherwise exhibit [47]. This begins to paint the picture as to why the banning of the fluoride wax for competition is an issue for snowboard organizations [48], [49]. All the variables discussed in the sections above show that there is no perfect solution for waxing, and that in addition to temperature, humidity, and snow grain size, there are likely more variables to consider, such as the friction abrasion or pollutants, wet suction, and electrostatic friction [32] [50].

3.7.7. Testing Methods

To test new boards in industry, the main method is field testing with professional athletes. However, research institutions equipped with more resources have been evaluating the performance of snowboard through scientific methods that are related to snowboard performance and tribology and are viable methods to consider when looking to improve the interface between the snowboard and snow.

Hasler and their team at University of Innsbruck created a novel tribometer, that is very representative in evaluating the coefficient of friction of a ski in a snow track, currently the most state of the art lab process [51]. In another study, acoustic sensors and accelerometers can be used along a snow track to understand the pressure distribution on the snowboard as well as instantaneous accelerations [35].

Surface roughness and contact angles are classic and useful measurements to have when evaluation friction [31], [42]. These values can be associated with the threshold of forces that need to be seen to induce and maintain motion. Incline plane testing as well as oscillating tests are utilized in the topography analysis [31]. Additionally, changes in speed of a sled with the material being analyzed can be used by conservation of energy [30].

In addition to objective studies, subjective results have been paired to performance to understand better how the boards perform with respect to rider's perceptions. Benchmarking variables such as stability, maneuverability, feedback, speed, and forgiveness are just a few factors that were assessed. Following the benchmarking, different stiffnesses and cambers were tested for different riding styles [52], [53].

3.8. The Proposed Experiment

Given the significant impact of the loss of fluorinated wax in the riding industry, it is imperative to explore ways to mitigate associated drawbacks. Identifying a material with characteristics akin to wax treatment, such as an increased contact angle, holds promise in narrowing the performance gap.

While numerous techniques have been scrutinized for their applicability in the field, this study will predominantly focus on traditional methods feasible within standard laboratories. Through minor adjustments, the objective is to enable standard tribology labs to evaluate snowboard performance without necessitating specialized testing tools. The research will unfold in a categorical process, as depicted in Figure 3.13. The tools employed in these studies will include a Micro-hardness testing machine, Scanning Electron microscope, confocal microscope, and automated droplet dispensers with a 50x camera lens. For laboratory testing, a tribometer with a cold temperature attachment, synthetic ice, and board samples, along with a slow-motion video and timer, will be utilized. In the case of upscale testing, the tools will be limited to inertial measurement devices, accompanied by timers, hygrometers, and thermometers.

Through this collection of experiments a standard Ultra-high Molecular Weight Polyethylene snow cross board will be compared to a new normal oriented fiber reinforced composite based snowboard. This material has been identified as having hydrophobic properties [54]. It conversely has been stated that polyethylene is “hydrophobic (and remains so under humid conditions), hard, highly elastic, can be smoothed and imprinted with different patterns, can be made porous, can easily be coated with binders, does not readily adhere to ice, and its friction is not greatly affected by surface contamination.” [28]. Findings should discuss the key differences between the materials, how their performance compares across increasingly representative tests, as well as a discussion on which characteristics are the most impactful for snowboard performance.

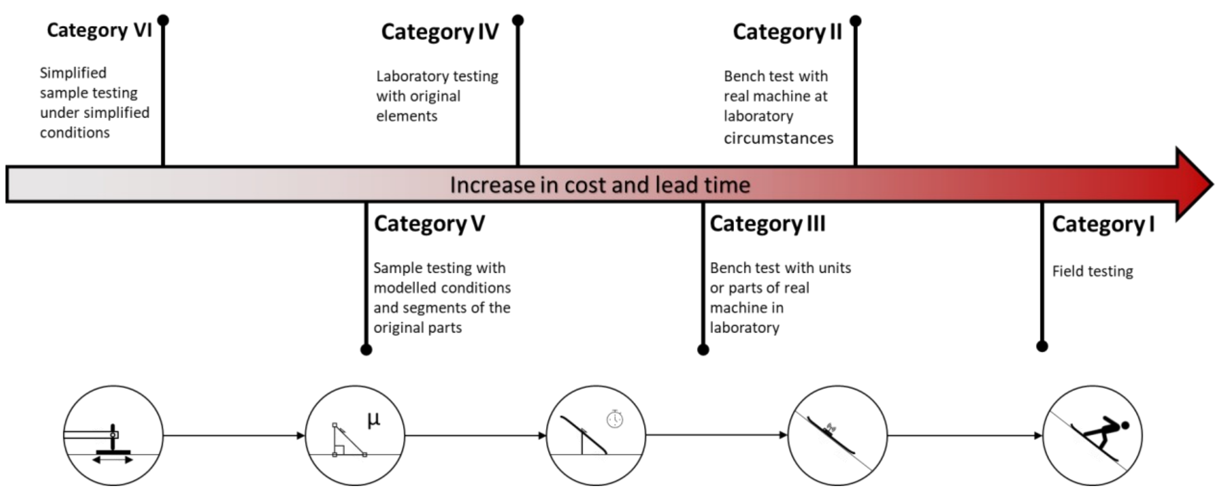


Figure 3.13 - Categorical evaluation of snowboard friction reflecting increasing representation.

3.9. Conclusion

As outlined in the review, the impact of tribology in sports extends beyond mere tangibility, significantly influencing the athlete's perception. It is imperative to consider interfaces from the most internal to the most external when designing experiments or products for optimal tribological performance. When dealing with human interaction, the weighting of factors like friction and lubrication tends to be slightly higher than wear, as wear closely correlates with product quality. Nevertheless, in products with lower usage, these weights tend to be more balanced.

Snowboards present a myriad of factors influencing their tribological characteristics due to various construction methods. Factors such as core materials, base roughness, base structure, and waxing techniques are among the numerous variables. Externally, the variability of snow introduces a dynamic environment, necessitating consideration of multiple solutions dependent on various factors. While custom equipment has been employed to enhance the accuracy of snowboard and snow interfaces, it comes with significant time and fine-tuning requirements. Establishing a simplified and categorical process for evaluating prototype snowboards in the laboratory and appropriately correlating these results with field test outcomes should yield a viable method for future snowboard tribology testing.

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Chapter

4. Development and critical evaluation of polymer matrix composites for green alternative replacement in alpine sports

In this chapter…

The experiment involves two snowboards: one with a base composed of Ultra-High Molecular Weight Polyethylene (UHMPE), and the other featuring a base made of Normal Oriented Fiber Reinforced Composite (NOFRC). The objective is to identify key performance factors by employing various techniques and correlating the performance of the boards through both in-laboratory and in-field test results.

4.1. Abstract

To address health and environmental concerns, the International Ski Federation (FIS) has imposed a ban on the use of fluorinated waxes for ski and snowboard preparation. Given the absence of the friction-reducing properties associated with this wax, the pursuit of alternatives becomes a high priority. While existing alternatives like hydrocarbon wax exist, they fall short in terms of effectiveness. Insights from aerospace research indicate that a normal-oriented fiber reinforced composite (NOFRC) performs well in sliding settings and demonstrates a hydrophobic tendency, suggesting its potential suitability for snowboard competition environments.

This study undertakes a comprehensive evaluation and comparison of a NOFRC base prototype snowboard's frictional performance against a standard snowboard base made of Ultra-High Molecular Weight Polyethylene (UHMWPE). The assessment follows an increasingly representative categorical process. Laboratory tests encompass characterization with Scanning Electron Microscopy (SEM), confocal laser scanning microscopy (CLSM), and contact angles. These in-lab experiments, tailored for this study, aim to compare performances under partial conditions resembling those seen in sports, investigating variables like temperature, lubrication, and board preparation. Tribometer tests were conducted using a ball-on-disk linear tribometer (Anton-Paar TRB3 tribometer), along with time trials of small samples on High-Density Polyethylene (HDPE) synthetic ice.

Field testing involves inertial measurement units (IMUs) placed on snowboards loaded with weight, sliding down a hill section, and 50-meter time trials by athletes from Canada Snowboard in both Chile and Quebec. The field evaluation seeks to mirror the lab results in a real-world snowboard environment. Comparison metrics include surface energy, material chemistry, roughness values, coefficients of friction, and trial time. The testing revealed that, in conditions devoid of subzero temperatures and water, NOFRC exhibits beneficial tribological characteristics. However, in instances of low temperatures and water, UHMWPE outperformed. The consistency of the categorical evaluation across phases and testing environments provides a valuable guide for assessing potential material alternatives in equipment production.

4.2. Introduction

The fluorinated wax ban was delayed due to the Covid 19 pandemic in addition to creating methods to verify compliance, finally taking effect during the 2023-2024 competition season. For environmental reasons, there is an industry need for an alternative solution to reduce friction while maintaining the same level of performance [1], [2], [3]. To manipulate the lubrication layer that forms during riding, the fluorinated waxes allow for maximum hydrophobic tendencies, that no longer are permitted.

To identify the key metrics impacting tribological performance, characterization of two materials was done before investigating the interactions. Properties measured were topology [4], stiffness, composition and surface energy. The first material, Ultra-High Molecular Weight Polyethylene (UHMWPE), is the most widely used base material in the industry because of its ideal sliding characteristics. It is hydrophobic, and can be manipulated with grinders to impose patterns, as well as porous to absorb other materials, the elastic yet hard nature is a benefit for many conditions [5]. The second material is an aerospace grade normal oriented fiber reinforced composite (NOFRC). It is designed to be a rigid material that can avoid wear at high temperatures [6]. In previous studies, it has been shown to be very hydrophobic. These results suggest that it might perform well in an environment that deals with management of water, like in snowboarding [7].

Additional influences independent of the snowboard base characteristics constituted by the material include snowboard preparation.[8], [9]. Preparation material and method has a tangible impact on the board-snow interface. Depending on the race day snow conditions, riders prepare boards differently. There is a growing amount of scientific backing to the techniques [10], [11]. Companies that produce waxes for the boards have a great understanding of these methods [9], [12]

These experiments leverage the available tools in the tribology labs at Concordia University in Montreal, in conjunction with professional riders, to produce performance results for both in-lab (small scale) and field (upscale) testing. The outcomes of these experiments will inform discussions on the significant distinctions between the materials, their comparative performance across progressively representative tests, and an emphasis on identifying the characteristics most influential for snowboard performance. The experimental process will adhere to the categorical format illustrated in Figure 4.1 below.

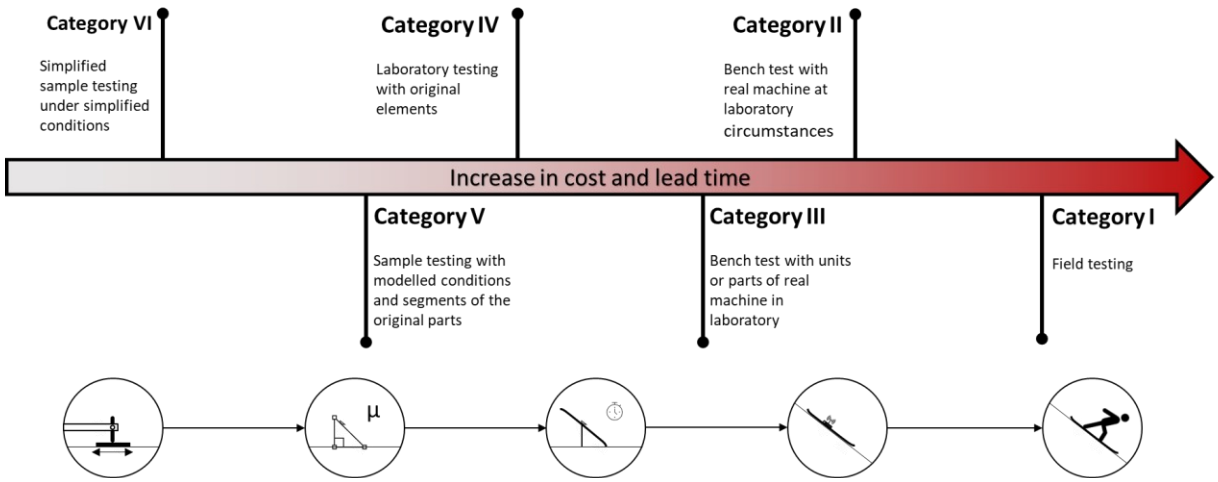


Figure 4.1 - Categorical evaluation of snowboard friction reflecting increasing representation

4.3. Experimental Procedures

4.3.1. Material development

4.3.1.1. Ultra-high molecular weight polyethylene (UHMWPE)

Ultra-high molecular weight polyethylene has become a widely used material for many industries. It spans from truck bed liners, machine part packaging, prosthetics, and the topic of discussion, sports [13]. The polymer is composed of two different phases: crystalline and amorphous. The crystalline is folded orderly chains, while the amorphous is the chaotically disordered. The high wear resistance is due to the entanglement of these layers. The ratio of phases can largely impact the mechanical properties of the material, allowing it to be “tuned” for ideal use cases [13], [14], [15]. Figure 4.2 shows the described composition of UHMWPE.

Previous research conducted on standard snowboards and skis states that benefits of the polyethylene structure include vibration dampening, modifiable surface (grinding), and is porous [5]. These are all optimizable attributes that can be helpful for the development of a snowboard. The UHMWPE used for this study is an industry standard, DuraSurf 4001 [16].

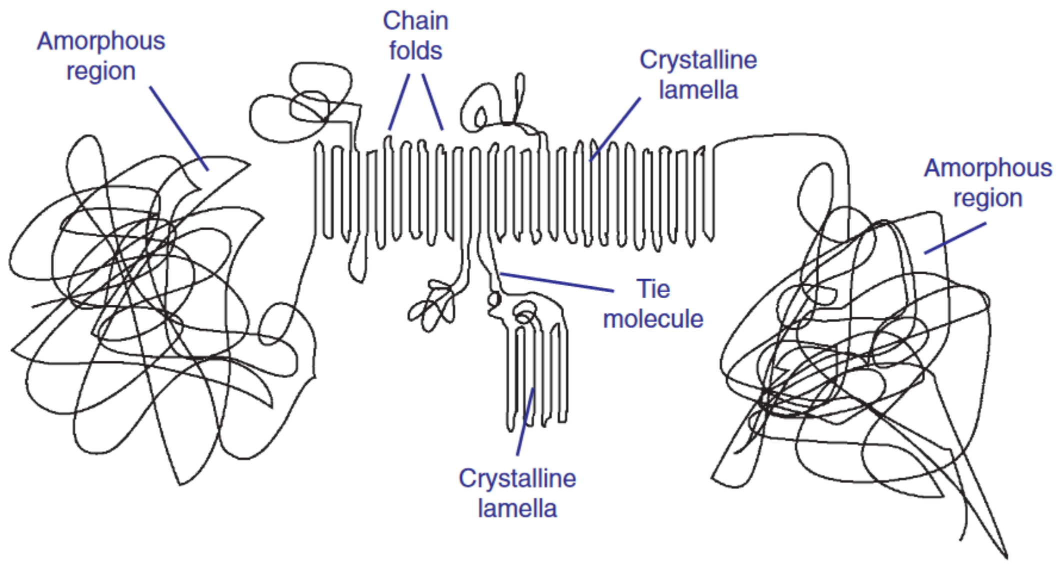


Figure 4.2 - Morphological features of UHMWPE [15]

4.3.1.2. Normal Oriented Fiber Reinforced Composite (NOFRC)

As in many other industries, composite materials have been appealing for strength to weight ratio, as well as more underlying benefits. The combination of the polymer and reinforcing fiber binding together in the same sheet material allows for a balance of properties to be created. In terms of composite's usefulness in tribology, the higher toughness, fatigue strength, high-temperature wear resistance as well as oxidation resistance are a few additional reasons as to which these materials are becoming more appealing for many applications. The nomral oriented fiber reinforced composite provided by Boston Materials is an innovative material that allows for fibers to be oriented perpendicular to typical composites, manufactured in an environmentally friendly method. Research has been started on the tribological effects of this orientation. So far, the findings tell that in load bearing instances the fiber orientation can create a non-directional friction and wear resistance benefit, as typical carbon fiber composites have more wear with parallel fibers than the normal fibers and anti-parallel fibers respectively [7]. In terms of snowboard applications, composites have an increasing modulus with the decrease of temperature. In real-world environments, cryogenic (-150C) is not seen, and therefore the low temperature, down to -50C, properties are more applicable in this use case [17]. With increasing hardness, smaller surface area is seen, and friction can be reduced. The NOFRC was created to work within the snowboard manufacturing process outlined below. This material is designed to operate at -40C without changes to the impact resistance [18].

4.3.1.3. Snowboard Manufacturing

Both UHMWPE and NOFRC boards were manufactured at Winterstick Snowboards headquarters in Maine, USA. Due to the composite sheet being added to the structure in place of the polymer, the steps and finishing for the novel material in the snowboard needed to be altered. Due to the layers of the composite limiting finishing techniques, the NOFRC board is slightly thicker than the standard board, which will affect its mechanical properties. Since the fibers in the layers would contaminate the grind wheel, a separate wheel needed to be used to finish the board so as to not contaminate others. The specific changes to the manufacturing process can be found elsewhere [19]. Figure 4.3 contains the finished NOFRC snowboard.

Figure 4.3 - Manufactured NOFRC Snowboard

4.3.2. Characterization Methods

As discussed, the materials that will be characterized are UHMWPE and NOFRC. In addition to evaluating the properties of the materials independently, a few samples will be surface prepped with industry standard hydrocarbon and fluorinated waxes. The tests with waxes will specify.

4.3.2.1. Hardness

The hardness of both the NOFRC and UHMWPE unprepped samples were taken using a Mitutoyo MVK-H1 Hardness Testing Machine. The load was set to 10g and held for 10 seconds before the indent size was measured and the Vickers Hardness values recorded.

4.3.2.2. Scanning Electron Microscopy (SEM)

The material composition and cross-sectional area images were taken using a Hitachi S-3400N Scanning Microscope. The samples were cut using a Struers Secotom-15 precision cutting machine. A 30A20 blade was used for both samples. Following this, the samples were mounted in epoxy resin before being polished in a Struers Tegramin-25 grinding and polishing machine. The samples images were then taken on the SEM machine.

4.3.2.3. Topography

Surface visuals and measurements were taken using confocal imaging with an Olympus LEXT OLS4100 laser confocal microscope. Both materials with and without waxing conditions were imaged for relative surface characteristics. Calibration was done before each sample image was taken, to ensure that the range of troughs and asperities were properly calibrated.

4.3.2.4. Contact Angles

For surface energy evaluation, contact angle measurements were recorded. Using a Rame-Hart automated water droplet dispenser, distilled water was dropped onto a sample in increments of 2.5 um, until a droplet of 25um was on the sample. The droplet was then retracted until the edges of the droplets slipped across the surface. During the process, images and video were captured with an iPhone 12 Pro camera using a Selvin 25X macro lens. Both materials with and without waxing conditions data was collected.

4.3.2.5. Snowboard Mechanical Testing

As is standard with snowboard testing done through Snowboard Canada, the board were tested in a lab in Canmore, Alberta before being deployed for field testing. These tests contained linear stiffness (flex), torsional stiffness obtained by hanging weights in specialized jigs, and surface roughness values Ra and Rz from a Mitutoyo roughness tester.

4.3.3. Testing Methods

4.3.3.1. Category VI – Pin on Disk Testing

To investigate the relative coefficient of the two board materials, samples of 1 inch by 1 inch were tested against a 6mm diameter alumina ball (AL203) using a ball-on-disk Anton-Parr TRB3 Tribometer. The samples were clamped into the machine and using a constant 5N of force and frequency of 1Hz, were tested for 20 meters. Each material was tested with different board preparation (no wax, hydrocarbon wax, fluorinated wax), and at two different temperatures (room temperature, -20 degrees Celsius). The temperatures were regulated by the Anton Parr LN2 cooling module Additionally, the materials at each condition were tested with and without water lubrication dropped onto the disk every 3 minutes, to more accurately represent the constant meltwater layer that is found when the second friction partner is snow.

4.3.3.2. Category V – Static Friction Test

Using High Density Polyethylene (HDPE) tiles, used as synthetic ice in room temperature environments, a downward slope was created. To gather relative information based on sliding performance against synthetic ice, the slope was lifted from flat until motion was seen by the samples. Additionally, once the starting angle was determined for both materials, the slope was set to an angle higher than that of the static friction, and the video was captured of the materials sliding to compare acceleration rates. The samples that were tested were non-waxed, hydrocarbon wax and fluorinated wax.

4.3.3.3. Category IV – Ice Test

To get an idea of the accelerations of the materials when low temperature and water was present removing influence of density, both boards were prepared with no wax, hydrocarbon wax and fluorinated wax were rigged upside down with a 30-degree angle. The boards were marked at the top for the starting position and again to show the finish line 34.5 inches down the board. With slow motion video taken from iPhone 12 Pro, the ice was placed at the starting position, and released. The relative performance for the ice to pass the finish line was verified with video and compared.

4.3.3.4. Category III / Category II – Simulated Snowboard Hill Test

To test the boards in a real-world environment, they were equipped with MoveSense accelerometers to compare accelerations down a slope. The data was collected at a sampling rate of 208 Hz. The boards were started at the same place, and nudged in the upwards direction to indicate when the trial began. The acceleration values were recorded for the trial, which ended when the board reached the bottom of the slope. The boards were tested on 3 separate occasions with different environmental conditions; 1. No wax preparation in -22°C snow conditions, 2. Hydrocarbon wax preparation in -15°C snow conditions, 3. Hydrocarbon wax preparation in -2°C snow conditions.

4.3.3.5. Category I – Performance Testing Under Relevant Conditions

The boards final stage of testing was through field testing with Canada Snowboard. These tests most accurately represent how the boards would perform in a competitive environment. They were tested in two locations with a 50m timed test. Observational feedback was also collected from the riders. The boards were tested for two days in Chile, and one day in Quebec with national team athletes.

The boards tested in Chile were tested on two separate days. 1. Low temperatures and very dry snow, 2. Temperatures closer to 0C and wet conditions. In both these days, the standard board had a factory structure with some hydrocarbon wax, while the CF-ZRT board was merely sanded without wax.

The boards tested in Quebec, Canada both had a standard structure imposed on them prepped with hydrocarbon wax. The conditions in Quebec were of dirty man-made snow, and with temperatures closer to 0°C.

4.4. Results

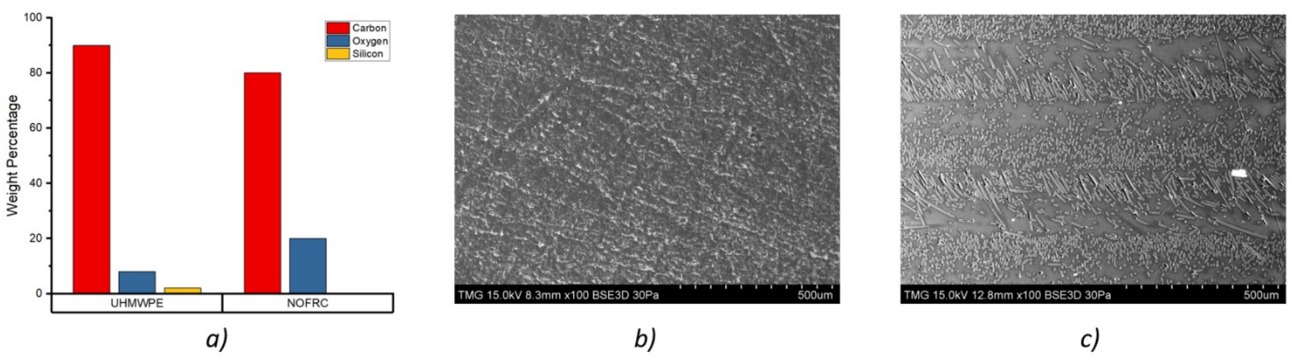
4.4.1. Characterization

4.4.1.1. Hardness

The NOFRC is a harder material than the UHMWPE. Their hardness values are approximately 100 and 10 HV respectively. Notably, there are inconsistencies in taking the hardness values for the NOFRC material, as it can vary depending on the volume of fibers present in the indentation region.

4.4.1.2. SEM

Figure 4.4 below displays the results from the SEM and EDS analysis. The chemical compositions of the materials are compared in weight percentages. The main differences in each materials composition can be distilled to a lower percentage of carbon and higher percentage of oxygen found in the NOFRC compared to the UHMWPE. The images shown illustrate the layered



construction of the composite with fibers in c) and the disordered surface that is a consequence of the material interlinking phases in b).

Figure 4.4 - a) EDS Analysis of cross-sectional area, SEM images at 100x magnification of b) UHMWPE cross section and c) NOFRC cross section

4.4.1.3. Topography

Surface images taken with the confocal microscope were processed through the LEXT processing software. The outputs were a topographic picture accompanied by roughness measurements. Due to the directionality of the motion for this application, line roughness was selected for analysis. The results indicate that between the two untreated materials, the UHMWPE has a much higher average surface roughness. Although higher roughness without preparation, there is not as much variability among the NOFRC in any preparation method and the wax prepared UHMWPE samples. Figure 4.5 below shows magnifications of the unwaxed samples.

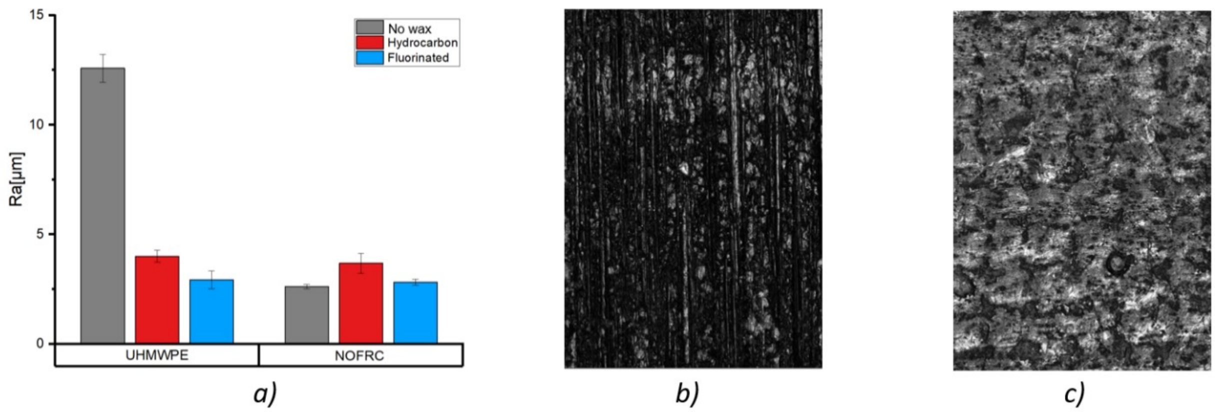


Figure 4.5 - a) Average line roughness values, confocal laser microscopy images of b) UHMWPE surface and c) NOFRC surface

4.4.1.4. Contact Angles

Using software [20], the advancing and receding angles can be taken from the images. With these values a critical force can be calculated using equation (8) below. Since the liquid used on both materials is the same, we can focus on the critical force ratio, F/γ_{lv}. This ratio relates the cohesive bonding forces within the liquid to the adhesion bonding from the liquid to the surface. It also can give relative difference in force required to move water along the surface [21].

$$F = \gamma_{lv}(\cos\theta_R - \cos\theta_A) \qquad (8)\ [7], [21]$$

As reported in figure 4.6, the NOFRC material has a lower critical force ratio than the UHMWPE. In terms of surface energy, the UHMWPE with fluorinated wax is closer in value to the unwaxed NOFRC material. Surface energy does not change much with the addition of hydrocarbon wax, however, it is notably reduced with fluorinated wax.

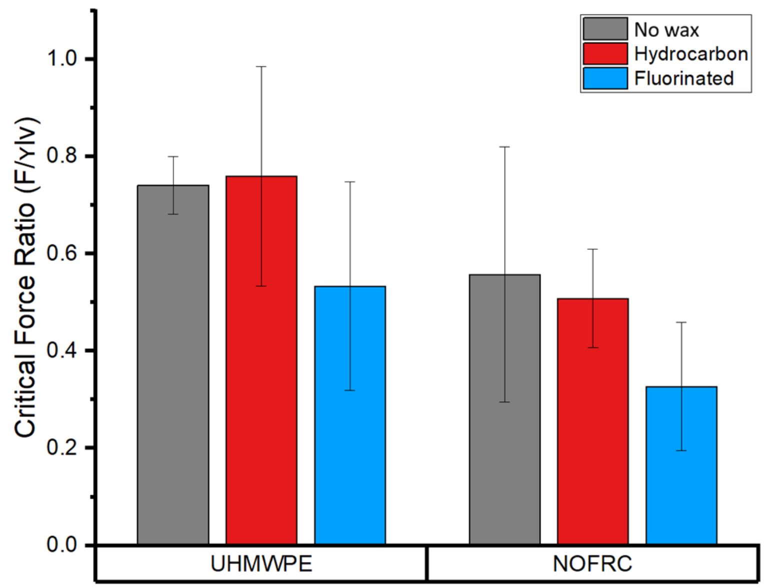


Figure 4.6 - Surface Energy Compared with Critical Force Ratio Values

4.4.1.5. Snowboard Mechanical Testing

Table 1 summarizes the differences in the boards manufactured. It is important to note that the NOFRC board did not have a structure imposed on it at the time of collection due to the unknowns related to grinding the normal oriented fiber base. These results will be useful in understanding the field test results.

Property	UHMWPE Base	NOFRC Base
Span (mm)	5	10
Flex (mm)	20.19	17.5
Torsion (Degrees)	4.8	3
Ra (µm)	2.4	1.5
Rz (µm)	11.2	10

Table 1 - Test snowboard mechanical properties

4.4.2. Testing

4.4.2.1. Category VI – Pin on Disk Testing

Figure 4.7 below shows all the coefficient of friction (COF) results. These values are the average COF seen between 10 and 20 meters of distance. These results can be compared across the sample preparation conditions as well as environmental factors (i.e. temperature and lubrication).

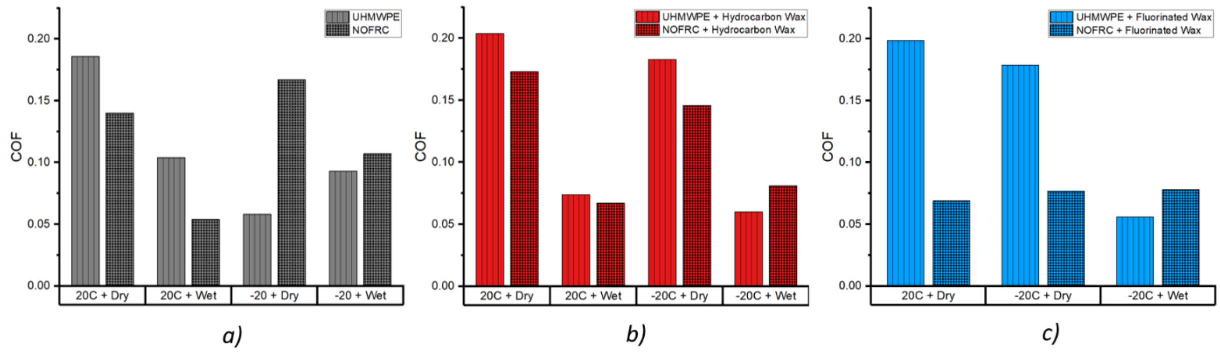
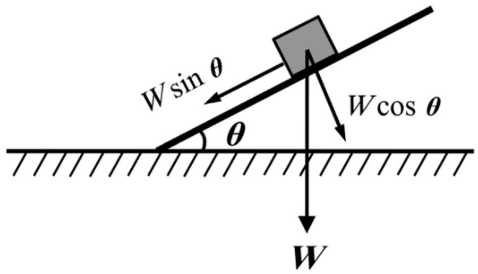


Figure 4.7 - Coefficient of friction for UHMWPE and NOFRC prepped with a) no waxes, b) hydrocarbon waxes, and c) fluorinated waxes

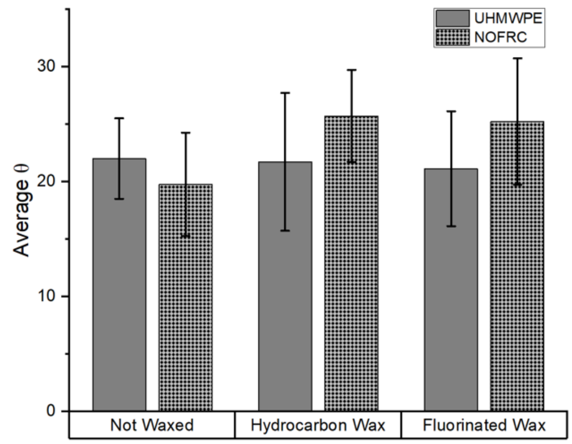
Key differences in performance are summarized in the following statements. In unwaxed conditions, the NOFRC has a lower COF in warm conditions, however the UHMWPE has a lower COF in cold conditions. When the samples are prepped with hydrocarbon wax, the NOFRC has a lower COF in dry conditions, but the COF values are much closer in wet conditions. Lastly, with fluorinated wax preparation, the NOFRC has a consistent performance, while the UHMWPE sample improves performance within the cold and wet environment.

4.4.2.2. Category V – Static Friction Test

The static friction test allowed simplified static and dynamic coefficients to be compared across different preparations interfacing with a synthetic ice material. In terms of static coefficients, figure 4.8 below shows that although the static coefficient of friction was lower for the NOFRC without waxes, in both waxed conditions, the static coefficient was lower for the UHMWPE.



a)



b)

Figure 4.8 – a) Slope schematic to determine static friction theta and b)Average theta to overcome static friction

The results from the sloped angle are tabulated in table 2 below. Higher acceleration in this test correlates with a lower dynamic coefficient of friction. With no waxes, the NOFRC had a higher acceleration than the UHMWPE. Like with the static coefficient values, we see that in both the Hydrocarbon and fluorinated wax conditions, the UHMWPE had a lower coefficient of friction.

Condition	No Wax		Hydrocarbon Wax		Fluorinated Wax	
Material	UHMWPE	NOFRC	UHMWPE	NOFRC	UHMWPE	NOFRC
Time (s)	3.44	2.59	3.11	3.39	3.72	4.12

Table 2 – Time trial values for board samples interfacing with HPDE

4.4.2.3. Category IV – Ice Test

The ice test allows for the trial times of the boards to be compared and observations to be made to determine which material was faster (having a lower time) for the given condition. Table 3 below indicates that with no waxes, the NOFRC material slid faster in most trials. For both waxed conditions, the faster sliding material shifts from the NOFRC to the UHMWPE.

Condition	No Wax		Hydrocarbon Wax		Fluorinated Wax	
Material	UHMWPE	NOFRC	UHMWPE	NOFRC	UHMWPE	NOFRC
Time (s)	.49	.48	.46	.63	.56	.71

Table 3 – Time trial values for ice interfacing with board

4.4.2.4. Category III / Category II – Simulated Snowboard Hill Test

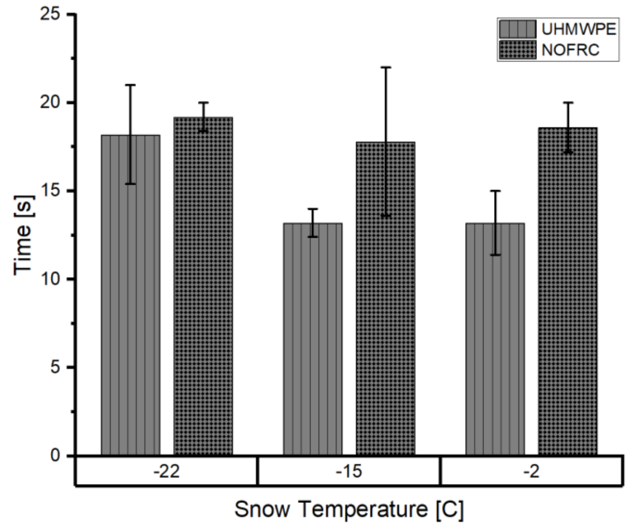


Figure 4.9 - Average Trial Time for Prototype Boards at Different Temperatures

Figure 4.9 shows the results from the riderless slope test. In all conditions, the UHMWPE had a quicker time for completion. As the temperature increased, there was a large difference seen in the times. The closest performance for the two boards interestingly was at the coldest temperature. As a reminder, at -22 degrees the boards were unwaxed, and with the other two conditions, both boards were prepped with hydrocarbon wax before testing. The NOFRC board appeared to often stick to the snow, with difficulty getting up to speed.

4.4.2.5. Category I – Performance Testing Under Relevant Conditions

Although the boards had some changes made to their preparation between tests, this did not significantly impact the field test results. The UHMWPE board finished the trials in a shorter amount of time. Again, the NOFRC board was described as sticky and slow to get started.

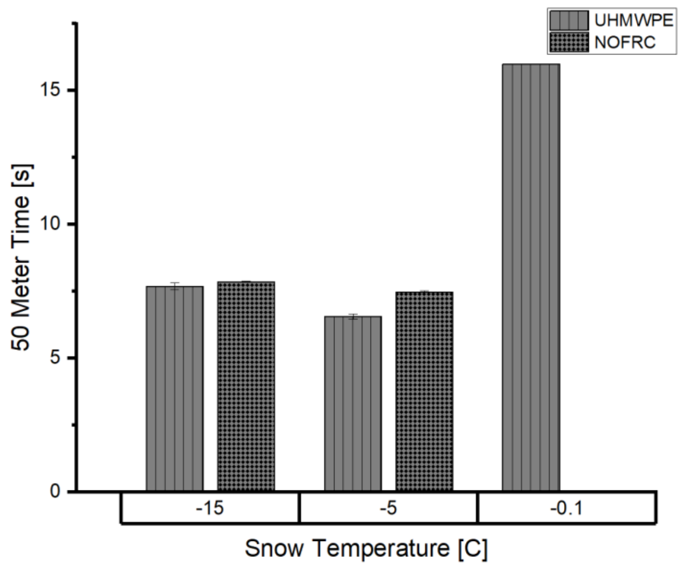


Figure 4.10 - Average 50m Trial Times in Athlete Slope Test

On the first day of testing figure 10 at -15C, with cold and dry conditions, although their times were not drastically different, the UHMWPE board performed better than the NOFRC. However, on the second day, -0.1C, the warmer and wet conditions had the NOFRC board completing the first segment in a significantly longer time and could not even complete the second segment. This is the cause of the missing bar in the -.01 condition. The riders commented that the NOFRC board did not get up to speed quickly and felt like it grabbed the snow underneath. Figure 10 at -5C shows the results from the boards when both prepped with hydrocarbon wax. Once again, the riders mentioned the NOFRC board gripped the snow. The results again show consistent lower times for trials with the UHMWPE.

4.5. Discussion

To determine how a new NOFRC snowboard base material compares to the traditional UHMWPE material, multiple phases of tests were completed. Both materials were tested with multiple surface conditions: no surface preparation, hydrocarbon wax, and fluorinated wax. They were also tested in multiple temperature and lubrication environments to highlight the key beneficial factors of each material. Table 4 below summarizes the parameters and results for each categorical test.

Category		VI	V	IV	III	II	I
Test		Pin on Disc	Angle Test	Ice Test	Simulated Hill Test		Field Tests
Surface Prep	No Wax	X	X	X	X		X
	Hydrocarbon Wax	X	X	X	X		X
	Fluorinated Wax	X	X	X			
Conditions*	Warm + Dry	X	X				
	Warm + Wet	X					
	Cold + Dry	X					
	Cold + Wet	X		X	X		X
Findings		• Unwaxed, NOFRC performs better • With H wax, UHMWPE has benefits when wet. • With F wax the UHMPE performance is enhanced with ice formation.	• The lower roughness has the lowest static COF • In motion, the UHMWPE has lower friction when waxed. Unwaxed the NOFRC has lower.	• NOFRC performs better with no waxes. • The ice test results correlate with the Angle test.	• UHMWPE board performs better in all snow conditions		• UHMWPE board performs better in all snow conditions

Table 4 – Categorical test results summary

In the warm and dry condition, the samples were compared to see how their coefficient of friction (static and dynamic) compare. As mentioned above, the UHMWPE was less performant without any waxes, which had been determined to reduce the roughness of the UHMWPE as displayed in figure 4.5a. Therefore, roughness of the material is what drives performance in these conditions, less interlocking of asperities allows for the NOFRC to move easier across the surface. When lubrication (water) is added to the system, creating a warm and wet environment, the results of the COF are much lower than without water. Furthermore, the hydrocarbon wax sufficiently equalizes the COFs. Again, the reduction in roughness from the UHMWPE is seen as a benefit in the warmer conditions. Notably, this wax is meant to shear allowing for the base surface to move.

The cold and dry conditions begin to closely reflect the results as seen in category I field testing. Interestingly, the NOFRC has a much higher COF without surface preparation, but still performs well with waxes. These findings indicate that the increase in stiffness of the NOFRC from the cold limiting the performance in cold environments without wax. Conclusively, the results in the cold and wet environment further the correlation between the lab testing and field testing. Figure 4.7 indicates that all COF are smaller for the UHMWPE, the category II results corroborate the results as the UHMWPE consistently has a smaller trial time than the NOFRC.

The higher stiffness and hardness characterization of the NOFRC board impacts the real area seen by the snow, changing the amount of friction generated. For all phases of testing, the lower temperature environments are best with the UHMWPE, suggesting that the drop in temperature has a positive impact on the sliding properties of the polyethylene, corroborating that polymers and composites tend to have an increase in strength and hardness as temperatures decreases [17]. Figure 4.11 below shows the interface of the snowboard and snow in cold environments with the formation of meltwater. The frictional force will be directly impacted by changes in stiffness. theoretically have a smaller area and friction with the NOFRC.

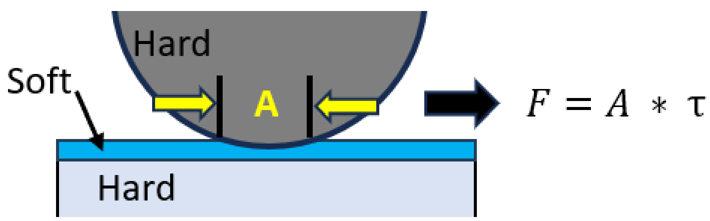


Figure 4.11 - Schematic of theorized interface for snowboards (adapted from [22])

Having higher hardness values at room temperature, although not race conditions, hint that the NOFRC will likely still have a higher relative hardness at lower temperatures. If we consider the hertzian contact equation (equation 9 and 10 below) from a sphere on a surface, it is apparent that the harder surface should benefit with less plastic deformation. Referring to equations 1 and 2, the area is a key factor in the friction force. Figure 4.12 below, with less deformation, would be expected to have a smaller frictional force with the NOFRC sample.

$$a = \left(\frac{3FR}{2E'}\right)^{1/3} \qquad (9)[23]$$

$$d = \left(\frac{2F^2}{E'^2 R}\right)^{1/3} \qquad (10)[23]$$

Differences in how the material will react can be seen when sliding against a harder material (Aluminum oxide). With a load of 5N, no significant wear is apparent in the two materials. Due to the lower load and test duration compared to other industries makes this not surprising. Since snowboards have a long lifespan, wear is not a factor in this testing. When coefficients are calculated, we see the UHMWPE has a much higher coefficient of friction in room temperature environments. The Phase II room temperature testing further supports that in dry conditions against a like material, the CF-ZRT will have lower static and dynamic frictional forces. This finding is what we would expect, however the influence of stiffness lessens when altering the temperature and lubrication of the system. The hertzian model does not account for these environmental factors and therefore the surface topology and hydrophobic properties are key to consider explaining performance differences.

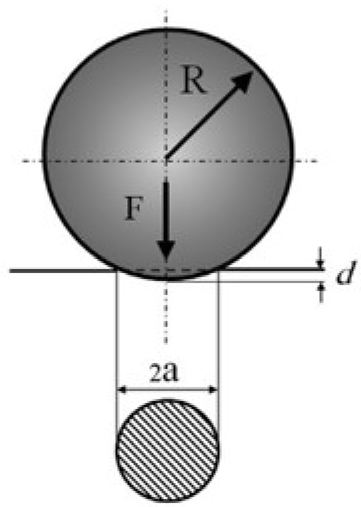


Figure 4.12 - Sphere point contact on flat schematic [23]

Through roughness characterization, figure 4.5a indicates the base material of the UHMWPE has a higher roughness than the NOFRC. With higher asperities, it factors into the increase of ploughing friction in the system. Although the stiffness influences the unwaxed room temperature results, by adding waxes and keeping the temperature constant, the results must change based on roughness. The lubrication layer of meltwater between the snowboard base and snow is vital for optimal frictional performance, and this is the key differentiator between what would be expected vs. what is apparent in snowboard-snow tribology [5]. Therefore, in cases where there is no lubrication layer such as cold, dry days found in the Phase III and Phase IV tests, this needs to be created through heating friction. This need is catered to by the higher roughness of the UHMWPE, and enhanced by the lower stiffness, allowing more area to be in contact ultimately creating a more easily lubricated system.

Not only does the topology of the board impact the meltwater lubrication created, but it can also impact how this fluid can move across the surface. In such a small thickness of water film relative to the length of the board, there is likely impact on the fluid film movement by the surface characteristics. Fluid mechanics dictates that streamlines of fluid will change their course, creating different types of flow depending on the features encountered [24]. Figure 4.13 below illustrates how these streamlines might vary between a rough walled surface and a smoother surface.

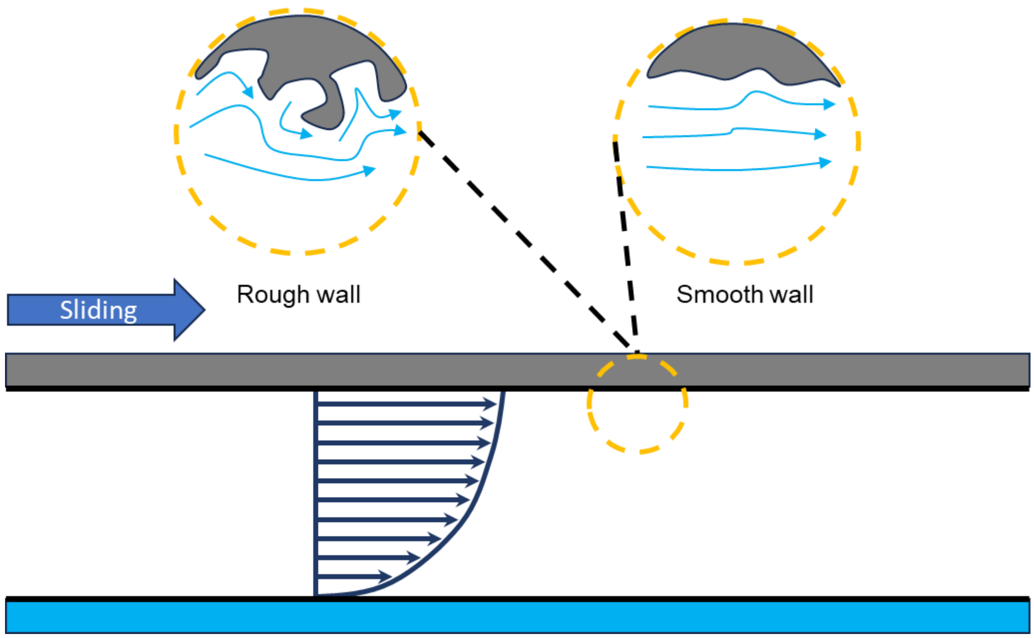


Figure 4.13 - Flow in a lubrication layer near a rough wall and smooth wall (adapted from [24])

The figure above shows the streamlines interacting with the natural surface, these will no doubt be altered with surface modifications. Wax preparation of the board creates topographical and energy related changes that will alter the performance of the board. Figure 4.14 below shows how the boards vary in their ability to hold wax. This phenomenon is no doubt a core factor in board performance with the wax surface modifications. The surface topology and ability to absorb of the UHMWPE material allows it to absorb the wax and share some properties. Contritely, the NOFRC material cannot accept the wax into the base and ultimately does not gain the benefits. The wax comes off in ribbons with the UHMWPE, and shard-like with the NOFRC, displaying the relative porosities. Figure 4.14 is the best example of the implications of prepping the boards with wax prior to measuring the friction. The graphs collectively show the impacts of different board preparation in different environments. In unwaxed conditions, the NOFRC board performs better in the warm conditions, however the UHMWPE is more performant, which can be linked to the increasing stiffness. However, by adding hydrogen wax to the system the roughness is modified, reducing the gap in performance. In both wet conditions, the UHMWPE increases performance with wax, which could be more in part to the surface energy changes from the wax.

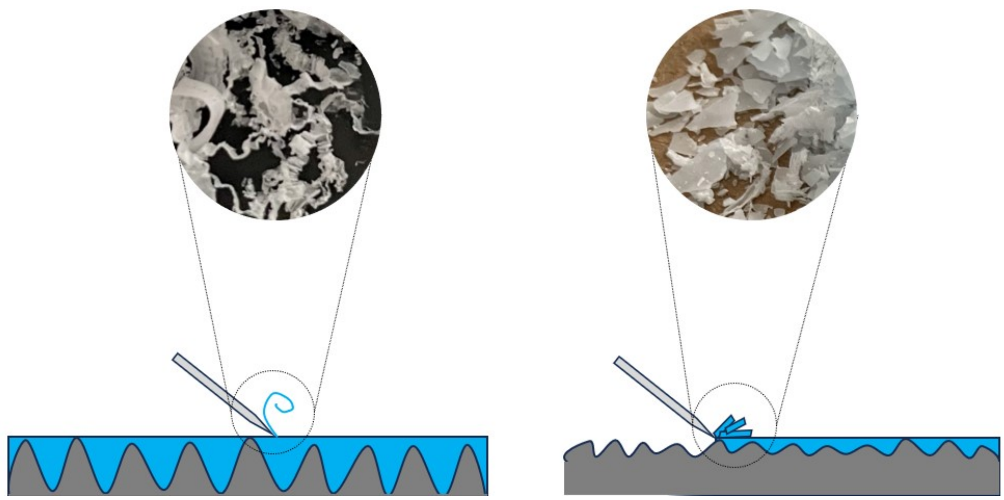


Figure 4.14 - Depiction of wax removal from a) UHMWPE and b) NOFRC

Comparing results from Categories V, and IV, the addition of wax has a detrimental effect on the NOFRC for initiating movement. The roughness values increase with wax, while decreasing for the UHMWPE sample. Furthermore, the dynamic friction slope test and ice test show benefits to the UHMWPE board when waxed. Ultimately, since the variation in roughness values are not significant between the waxed samples, these results are likely also tightly linked to the surface energies of the boards.

However small the impact of these changes, it will influence the full board performance. The base roughness values would imply smoother streamlines for the NOFRC board, reducing the drag as shown in figure 13. Since we do not see this board performing better in these environments, there must be more value in efficient management of the layer of lubrication. For racing, the boards are prepped for environmental conditions, which will alter the roughness values. The porous nature will create areas of multiple properties, allowing for a blend of topological and surface energy benefits.

Typically, materials with a finer surface have higher surface energies and are hydrophilic. Figure 4.6 verifies that the NOFRC has lower surface energy, The UHMWPE has a higher surface energy with a higher roughness. Furthermore, both surfaces find about the same amount of surface energy with hydrocarbon wax, but a decrease with the addition of the fluorinated wax. These values are not outside what is expected with the intention of each wax [9]. These results indicate why the fluorinated wax is a benefit to riders for wet conditions.

Materials that can better manage the lubrication created will have better performance. Interestingly, the results show that a more hydrophobic base in real environments does not perform as well as the alternative. The reason that a more hydrophobic surface would be less performant in a wet environment is due to the relative surface energies and a hydration layer that can be created on the base of the snowboard. UHMWPE is a good material for tribological applications due to its hydrophobic tendencies, but also for its porosity, allowing variability in the properties of the base surface. This trait allows an effective hydration layer to be created, permitting the material to glide smoothly across the surface instead of plowing the lubrication layer. Figure 4.15 below contains a schematic of the impact of a hydration layer, and why a more hydrophobic board will run into higher resistance with higher lubrication. Therefore, we see that the expected benefit of hydrophobicity has limits in the way the board manipulates the water created from friction. Since the NOFRC board cannot accept the properties of the waxes, it will not be able to adapt to different riding conditions. For non-waxed bases, the roughness of the UHMWPE allows for more mechanical interlocking of the water/ice, allowing for a better lubrication layer, however the NOFRC can't form a layer due to roughness and contact angles. Similarly, by accepting and locking onto the wax, the UHMWPE can exhibit these beneficial properties in practice.

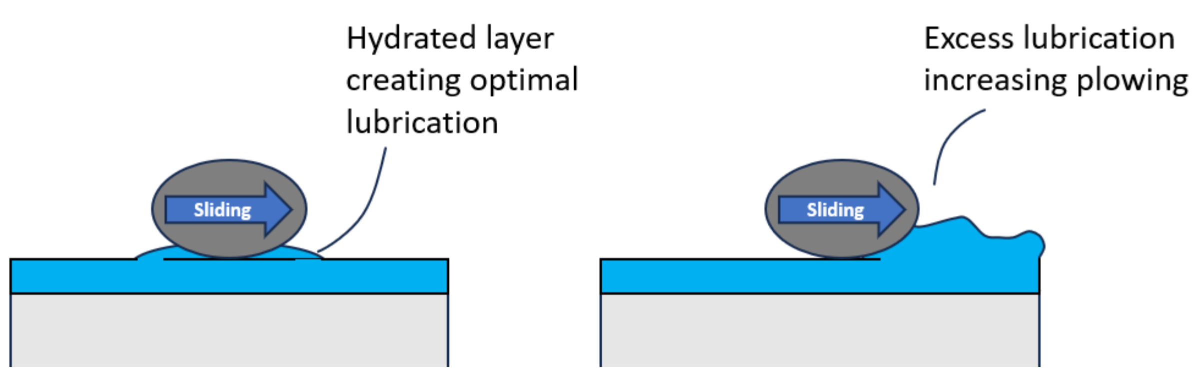


Figure 4.15 - Schematic of hydration layer and plowing of water lubrication (adapted from [25])

Figure 4.16 below indicates the agreement between the categorical II through category VI tests and category I results. Correlations between the field testing results and lower scale tests can be visualized by each test condition specified, highlighting the requirement of cold temperatures and lubrication. These would be the only conditions found in a race environment, as the warm conditions for lab testing do not include snow interfaces with these testing methods.

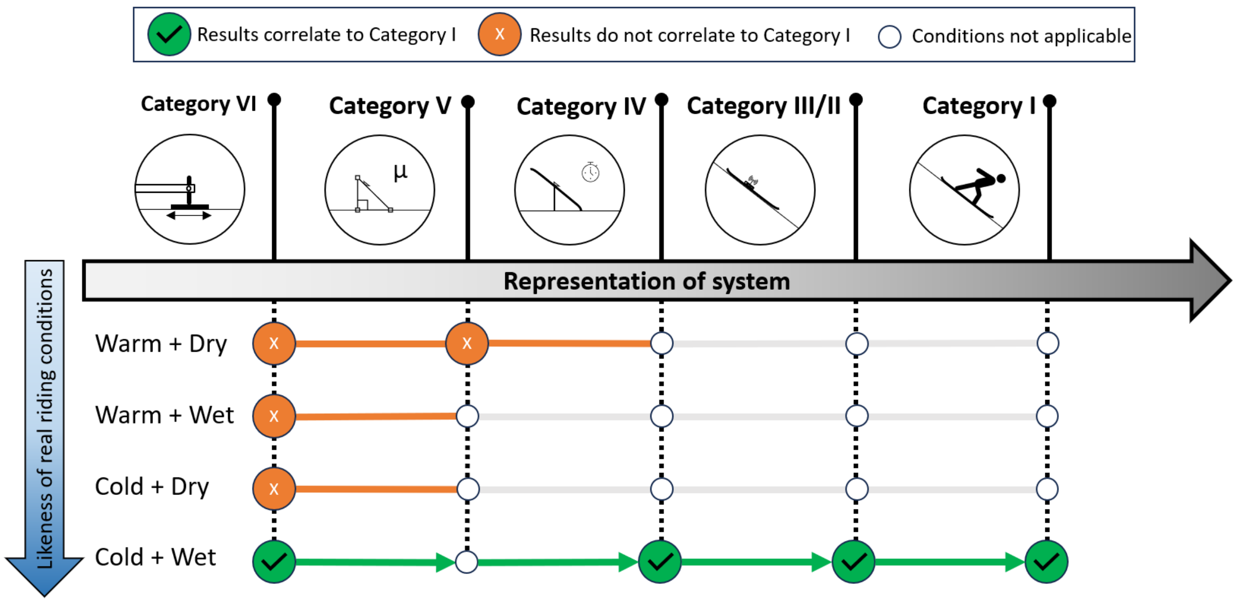


Figure 4.16 – Correlation of categorical test results

As a result of the complexity created by the environment variables, it becomes difficult to source just one solution for reducing friction. It is clear that a balance of properties is necessary to optimize the mechanisms for sliding in different conditions, especially in cold wet environments. Based on the evidence discussed, it appears that for conditions most representative of snowboard racing UHMWPE has the better blend of characteristics. Understanding why this combination is successful will be key to future snowboard materials engineering.

4.6. Conclusions

These findings show that the Ultra-High Molecular Weight Polyethylene is still the superior material to the Normal Oriented Fiber Reinforce Composite for snowboard base material due to the optimal characteristics in terms of material stiffness, surface roughness, and surface energy. The higher stiffness of the NOFRC, although beneficial in room temperature tests, becomes detrimental when more friction is required against snow to create a meltwater layer of lubrication, needed for sliding. The combination of lower stiffness and higher roughness of the UHMWPE, although typically not desirable traits for reducing friction, are effective in snowboarding. The hydrophobicity of the NOFRC board, that was hypothesized to improve performance in wet conditions was not the case, as a hydration layer on the surface aids in smooth sliding on the surface of lubrication. The porous UHMWPE allows for areas of different properties to be created on the board (i.e., lower roughness, lower surface energies) that allows for a balance of properties, and manipulation of optimal water layer thicknesses required in snowboard-snow sliding. In summary, snowboard design requires bases to be in an optimal range across multiple properties. These properties and test show that lab tests can correlate to the upscale tests when the conditions for testing are in cold and wet environments, most like those during real life competitions.

4.7. Future work

As this experiment concludes that the NOFRC prototype board that was manufactured does not perform as well as the standard UHMWPE board in specified conditions, there are still valuable insights to drive further investigation on the matter. Although six categories of testing were completed, there are gaps (see table 4) of environmental conditions for different categorical tests. These may be more challenging to create as they are less natural, and may require more funding to research, but would allow for an even more granular scaling of characteristic impacts.

In terms of mitigating the performance loss of fluorinated wax, alternative wax solutions should be tested, as UHMWPE has shown clear benefits in being a dominant base material and interacts quite well with wax surface treatments. New materials being integrated on a snowboard require modifications to manufacturing, which can be costly, and delay testing. Creating a method to test materials at the category I and II levels without having to manufacture an entire board would be much more efficient to evaluate the performance of different material and surface treatment combinations.

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Chapter

5. Conclusion and Future Work

In this chapter…

Overall findings are noted, along with proposed future work in the area.

5.1. Conclusion

The research findings encapsulate insights into sports tribology, culminating in the examination of snowboard tribology, specifically comparing a UHMWPE board against a NOFRC prototype board. Chapter 3 sheds light on the holistic picture of an athlete and the potential tribology mechanisms encountered during competition. Examining tribological aspects from skin to garments and equipment that interface with the environment, understanding the cumulative implications is key for a comprehensive grasp of performance. The deeper exploration of snowboarding tribology, including its governing mechanisms and the intricacies of the manufacturing process, serves as a driver for experimentation, providing valuable direction for future growth and development in the sport. Results indicate that optimal meltwater is crucial for minimizing friction, and the board itself must contribute to its creation. Multiple variables, such as composition, stiffness, roughness, and surface energy, are thoroughly investigated through a categorical process that utilizes SEM imaging, confocal laser scanning, and tribometer tests. This process begins with small sections of the snowboard base material in lab settings and concludes with the evaluation of full boards in real-world environments.

The objectives of this research encompass a holistic understanding of sports tribology, with a specific focus on snowboarding tribology. The findings provide crucial insights and directions for optimizing snowboard performance, emphasizing the importance of various material and design considerations. This process was found to show repeated themes across categorical testing making it a viable testing methodology.

The following statements outline the subobjective achievements.

- The environmentally friendly alternative was identified as a Normal Oriented Fiber Reinforced Composite and tested against the standard Ultra-High Molecular weight board.
- This alternative showed some benefits at room temperature small scale testing; however, the benefits were minimized in realistic snowboarding conditions.
- Although not performant now, NOFRC would have better results by tuning the roughness without surface preparation, imposing a structure on the material, or creating a mechanism to interlock wax like materials to the surface as a few possible improvements.

In addition, there is a growing amount of research being done in the tribology field for sports. Some findings important for future snowboard or ski related research are the following.

- Optimal meltwater is needed for ideal friction.

- Friction needs to be enough to generate frictional heating and start the meltwater lubrication.
- The board needs to adhere to the water a certain amount, to allow for a hydration layer, and avoid an increase in plowing friction.
- Stiffness of the board can be a factor on area of contact, so higher stiffnesses will have lower areas of contact (with lower roughness it becomes hard to generate friction)
- Drag in the shearing fluid can be a factor in the friction seen at higher speeds and should be investigated further.
- To benefit from wax preparation, the board needs to have the ability to absorb properties of surface treatments.

Although certain studies have looked at snow and ice friction [31], as well as material properties impacting the coefficient of friction [17], the dynamic nature of the snow creates difficulty in manufacturing the ideal finish of the board in one material for now. Unfortunately, using this new hydrophobic composite is not the single solution, the process in which this was deciphered as well as the findings are valuable pieces in the map of improving performance of a snowboard with the limitation of non-fluorinated waxes. Further research should be done with alternative materials and preparation to deepen knowledge in this field.

5.2. Future Directions

Suggestions for future research include the following.

- Drag research – With the different roughness values of snowboards, these have a vital impact on the friction values during sliding. When the optimal layer of meltwater is present, how does this layer interact with the board, and can the roughness of the board.
- Optimized zones for the cross-country skis – Although the NOFRC material did not perform as well as the UHMWPE in cold or wet conditions, there can be benefits for other use cases. For cross country skis, some friction can be beneficial to create motion from a stop.
- Optimization of roughness (surface grinding) – structure that is imposed on the boards is a key way to manage the water that is generated or present during sliding. Deeper analysis would be beneficial to quantify the impacts of different structures on a standard UHMWPE board for different conditions.

- Creating new wax (fluorine-free) – a more chemical approach to improving snow friction would be to look into wax alternatives that perform as well as the fluorinated waxes without the harmful elements.
- Methods for research – although the aim of this research was to create a process from small scale to field testing for evaluating test boards. There are still some missing boxes, although more unnatural environments. More Category V, IV, III and II testing methods should be explored with additional conditions.
- Protocol for testing new board materials – A limitation on testing prototype board is the time and cost to manufacture entirely new boards. Although vital for competition boards, quantitative tests would benefit from a quicker prototype testing mechanism to quickly try different materials on a full-size snowboard.

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