BIOMECHANICAL PERFORMANCE FACTORS OF SLALOM WATER SKIING

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ABSTRACT

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The instrumentation and methodology of this study provided quantitative data for a group of six advanced slalom skiers. Rope load, skier velocity, ski roll, ski acceleration and ski deceleration were calculated during the deep water start and cutting portion of a slalom run. Four different ski designs were tested in order to determine if the test subjects were able to achieve a different level of performance on each ski. Through a statistical analysis there was enough evidence to suggest that a different performance was achieved between the skis, for rope load and peak roll. There was also enough evidence to suggest that the skiers were achieving different overall levels of performance. The analysis procedure of this study achieved the goal of proving that it could be used to improve coaching capabilities and product design in the water ski industry.
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Table of Contents

Acknowledgments........................................................................................................ iii
Table of Contents........................................................................................................ iv
List of Figures.............................................................................................................. vi
List of Tables ................................................................................................................ x

Chapter 1: Introduction and Background........................................................................ 1
  1.1 The Basics of Water Skiing.................................................................................... 2
  1.2 Coaching................................................................................................................ 6
  1.3 Instrumentation....................................................................................................... 7
  1.4 Methodology.......................................................................................................... 8
  1.5 Thesis outline......................................................................................................... 11

Chapter 2: Literature Review.......................................................................................... 13
  2.1 Literature Review................................................................................................... 14

Chapter 3: Methods and Instrumentation used for Biomechanical Analysis of Slalom Water Skiing ................................................................. 23

Abstract......................................................................................................................... 25
  1 Introduction and Background.................................................................................. 26
  2 Methods................................................................................................................... 30
  3 Results.................................................................................................................... 39
  4 Discussion............................................................................................................... 44
  5 Conclusion.............................................................................................................. 47
  6 Acknowledgements................................................................................................. 48
  7 References............................................................................................................. 48

Chapter 4: Water Skiing Biomechanics a Study of Advanced Skiers .............................. 49

Abstract......................................................................................................................... 51
  1 Introduction and Background.................................................................................. 52
  2 Methods................................................................................................................... 54
  3 Results.................................................................................................................... 61
  4 Discussion............................................................................................................... 69
  5 Conclusion.............................................................................................................. 76
  6 Acknowledgements................................................................................................. 78
  7 References............................................................................................................. 78

Chapter 5: Biomechanical Analysis of Slalom Water Skiing: an in-depth look at a slalom cut ................................................................................................................. 79

Abstract......................................................................................................................... 81
  1 Introduction............................................................................................................. 82
  2 Methods................................................................................................................... 85
  3 Results.................................................................................................................... 89
  4 Discussion............................................................................................................... 105
  5 Conclusion.............................................................................................................. 111
  6 Acknowledgements................................................................................................. 112
  7 References............................................................................................................. 112

Chapter 6 – Conclusion and Future Considerations ................................................... 113
6.1 Conclusion and Future Considerations ................................................. 114
References .......................................................................................... 116
Appendices .......................................................................................... 119
  Appendix A: Sample calibration procedure for the load transducer......... 120
  Appendix B: Sample qualitative survey .................................................. 122
  Appendix C – Ski Survey Results.......................................................... 127
List of Figures

Chapter 3

Figure 1: a) IMU system in its housing strapped to the front of one of the skis. b) IMU and its transceiver system mounted in plastic box ........................................... 32
Figure 2: GPS unit wrapped in plastic and mounted in the helmet ...................... 33
Figure 3 - Diagram of slalom course including entrance gates ( x ), skier path and buoys 1 – 6 ( o ) and sample dimensions [“International Waterski & Wakeboard”, 2010]. ............................................................ 37
Figure 4: Example rope load, skier velocity and boat velocity data for one test run. Major activities include: start up (SU), entrance cut (EC), slalom turns (ST) and boat turn around (BTA). ............................................................... 40
Figure 5: Example ski pitch, roll and heading data for one test run. Major activities include: start up (SU), entrance cut (EC), slalom turns (ST) and boat turn around (BTA). ............................................................... 41
Figure 6: Example ski acceleration/deceleration data for one test run. Major activities include: start up (SU), entrance cut (EC), slalom turns (ST) and boat turn around (BTA). ............................................................... 41
Figure 7: Example IMU data signal reception a) good b) bad and c) intermittent. Loss of signal is represented as horizontal lines of repeated data. ......................... 43

Chapter 4

Figure 1: Example ski profile .................................................................................. 56
Figure 2: Diagram of slalom course including entrance gates ( x ), skier path and buoys 1 – 6 ( o ) and sample dimensions [“International Waterski & Wakeboard”, 2010]. ........................................................................ 57
Figure 3: Sample of typical data collected during one experimental run. Major activities include: start up (SU), entrance cut (EC), slalom turns (ST) and boat turn around (BTA). ............................................................... 62
Figure 4: Summary of skier’s maximum rope load results for deep water starts. The highest average was 2.64BW and lowest average was 1.92BW. There was a significant difference between the skiers (p<0.0001). Error bars represent the pooled standard error. ................................................................. 63
Figure 5: Ski’s overall average peak rope load during deep water starts. The highest average was 2.41BW and lowest average was 2.16BW. There was no significant difference between the skis (p=0.0993). Error bars represent the pooled standard error. ................................................................. 64
Figure 6: Skier’s overall average turn peak rope load for dominant and non-dominant turns. The highest and lowest dominant turn average was 2.63BW and 1.54BW. The highest and lowest non-dominant turn average was 2.51BW and 1.53BW. There was a significant difference between the skiers (p<0.0001). Error bars represent the upper and lower confidence intervals........ 65
Figure 7: Ski’s overall average turn peak rope load for both dominant and non-dominant turns. The highest and lowest dominant turn average was 2.15BW
and 2.08BW. The highest and lowest non-dominant turn average was 2.05BW and 1.93BW. There was a significant difference between the skis (p=0.0244). Error bars represent the upper and lower confidence intervals. Figure 8: Skier’s overall average peak skier velocity for all turns. The highest average was 133.88% and lowest average was 118.18%. There was a significant difference between the skiers (p<0.0001). Error bars represent the pooled standard error. Figure 9: Ski’s overall peak skier velocity during cutting for all turns. The highest average was 129.02% and lowest average was 128.59%. There was no significant difference between the skis (p=0.9309). Error bars represent the pooled standard error.

Chapter 5

Figure 1: Diagram of slalom course including entrance gates (x), skier path and buoys 1–6 (o) and sample dimensions [“International Waterski & Wakeboard”, 2010]. Figure 2: Sample ski profile. Figure 3: Typical left turn ski roll, ski acceleration, skier velocity and rope load for subject 11, who had an overall success rate of 88.7%. The five phases of a slalom cut can be identified: approach, apex, exit, wake crossing (WC) and next turn initiation (NTI). Figure 4: Typical left turn ski roll, ski acceleration, skier velocity and rope load for subject 15, who had an overall success rate of 0%. The five phases of a slalom cut can be identified: approach, apex, exit, wake crossing (WC) and next turn initiation (NTI). Figure 5: Subject overall average integral of roll and peak roll for dominant turns. The highest averages were 109.40º·s and 59.41º, and lowest averages were 68.79 º·s and 47.03 º. There was a significant difference between the skiers for both performance parameters (p<0.0001). Error bars for the integral represent upper and lower confidence intervals and error bars for the peak represent pooled standard error. Figure 6: Subject overall average integral of roll and peak roll for non-dominant turns. The highest averages were 104.68º·s and 56.80º, and lowest averages were 67.33 º·s and 44.52 º. There was a significant difference between the skiers for both performance parameters (p<0.0001). Error bars for the integral represent upper and lower confidence intervals and error bars for the peak represent pooled standard error. Figure 7: Ski overall average integral of roll and peak roll for dominant turns. The highest averages were 96.44º·s and 54.18º, and lowest averages were 87.83 º·s and 52.96 º. There was a significant difference between the skis for peak roll but not for integral of roll (p=0.0014 and p=0.3464). Error bars for the integral represent upper and lower confidence intervals and error bars for the peak represent pooled standard error. Figure 8: Ski overall average integral of roll and peak roll for non-dominant turns. The highest averages were 88.47º·s and 52.51º, and lowest averages were
83.42°·s and 48.92°. There was a significant difference between the skis for peak roll but not for integral of roll (p=0.0014 and p=0.3464). Error bars for the integral represent upper and lower confidence intervals and error bars for the peak represent pooled standard error. 

Figure 9: Subject overall average integral of deceleration for dominant and non-dominant turns. The highest and lowest dominant turn results were -9.19 and -4.34m/s^2·s. The highest and lowest non-dominant turn results were -9.26 and -4.35 m/s^2·s. There was a significant difference between the skiers (p<0.0001). Error bars represent pooled standard error.

Figure 10: Ski overall average integral of deceleration for dominant and non-dominant turns. The highest and lowest dominant turn results were -7.48 and -6.77m/s^2·s. The highest and lowest non-dominant turn results were -7.96 and -7.61 m/s^2·s. There was no significant difference between the skis (p=0.1341). Error bars represent pooled standard error.

Figure 11: Skier overall average peak deceleration for all turns. The highest average was -12.46m/s^2 and lowest average was -8.053m/s^2. There was a significant difference between the skiers (p<0.0001). Error bars represent the pooled standard error.

Figure 12: Ski overall average peak deceleration for all turns. The highest average was -11.22m/s^2 and lowest average was -10.39m/s^2. There was no significant difference between the skis (p=0.1134). Error bars represent the pooled standard error.

Figure 13: Skier overall average integral of acceleration and peak acceleration for dominant turns. The highest averages were 6.18m/s^2·s and 13.60m/s^2, and lowest averages were 2.08m/s^2·s and 6.06m/s^2. There was a significant difference between the skiers for both parameters (p<0.0001). Error bars represent upper and lower confidence intervals.

Figure 14: Skier overall average integral of acceleration and peak acceleration for non-dominant turns. The highest averages were 5.50m/s^2·s and 11.62m/s^2, and lowest averages were 2.07m/s^2·s and 5.16m/s^2. There was a significant difference between the skiers for both parameters (p<0.0001). Error bars represent upper and lower confidence intervals.

Figure 15: Ski overall average integral of acceleration and peak acceleration for dominant turns. The highest averages were 4.92m/s^2·s and 11.18m/s^2, and lowest averages were 4.75m/s^2·s and 10.67m/s^2. There was no significant difference between the skis for both parameters (p=0.9314 and p=0.9326). Error bars represent pooled standard error.

Figure 16: Ski overall average integral of acceleration and peak acceleration for non-dominant turns. The highest averages were 4.54m/s^2·s and 9.95m/s^2, and lowest averages were 4.18m/s^2·s and 9.13m/s^2. There was no significant difference between the skis for both parameters (p=0.9314 and p=0.9326). Error bars represent pooled standard error.
Appendix A

Figure 1: Calibration curve generated for day 1. The linear model equation was used to determine rope load given the voltage output during each experimental test run.
List of Tables

Chapter 4

Table 1: Summary of human participants used in the study ........................................ 55
Table 2: Summary of ski models used ........................................................................ 56
Table 3: Summary of completed turns and number of successful turns for each subject ........................................................................................................... 63

Chapter 5

Table 1: Summary of the recruited human participants ............................................. 85
Table 2: Summary of the four ski models used .......................................................... 88
Table 3: Success Rate results of each skier ................................................................ 90

Appendix C

Table 1: Summary of ski survey results ..................................................................... 127
Chapter 1: Introduction and Background
1.1 The Basics of Water Skiing

Water skiing has been traced back to the early 1920s when skis were simple pine boards with leather straps. Early product development and growth of participation was mainly driven by the increasing availability of high performance boats. Since then it has grown to approximately 10 million participants in North America and has proof of growing international participation by its introduction into the Pan American Games in 1995 [SGMA, 2003; “Pan American Games”, 2011]. The International Waterski and Wakeboard Federation is the international governing body and Water Ski and Wakeboard Canada is the national governing body.

Water skiing is often seen as a luxury sport because it requires a unique set of equipment and access to a body of water. The equipment basics include a power boat, water skis and tow rope. For beginner skiers the only requirements for the power boat being used is that it has enough horsepower to pull the skier out of the water and maintain a speed high enough such that the skis ride on top of the water. This is usually in the range of 40-50 km/h, depending on skier weight. As skiers begin to participate more frequently and their skill level increases, there is the desire for higher-end equipment including tow boats that have been designed specifically for skiing. The fundamental components of a water ski are the ski, bindings and fin. Beginner skis are constructed from a reinforced composite material, with rubber adjustable bindings. Higher-end performance skis will often have a more complex construction with an emphasis on being lightweight, with a reinforced core. Binding construction also becomes more complex with the emphasis on being
lightweight, tight fitting and having plenty of ankle support. Fins on recreational skis are very simple with no adjustability but on higher-end skis they are fully adjustable and include a smaller horizontal wing that helps decelerate the ski. This allows the skier to personalize the way the ski handles to suit their individual skiing style. A tow rope consists of two components, the rope itself and a handle, and at full length will be 23 m long. All skill levels will use rope woven from a synthetic material; however, more experienced skiers will want a rope that allows for minimal stretch and has removable lengths so it can be shortened. Recreational rope handles will have an injection molded rubber grip, whereas a higher-end handle will often have an aluminum bar with a soft rubber molded onto it, making them stiff and lightweight.

Like most sports, water skiing has several stages of participation for a variety of skill levels. In the early levels of participation water skiers will use two skis, one on each foot. Learning how to get up out of the water is the first step for a beginner water skier and once up on the skis, the main goal is to stay standing on the water directly behind the boat. As the skier’s comfort grows they progress to being able to use their edges and steer themselves out of the wake on either side of the boat. When using two skis has been mastered, a water skier will progress to slalom skiing, which is using only one ski with both feet attached, one in front of the other. Slalom skiing is considered to be the intermediate/advanced level of water skiing. In the beginning stages of slalom skiing, the skier will get up on two skis and drop one once they have stabilized. This allows the skier to get comfortable riding on one ski before they learn how to do a slalom deep water start. Once again in the beginning stages of slalom skiing the skiers main goal is to get
comfortable staying behind the boat and then progress to using their edges to steer themselves out of the wake. As comfort and skill increases the skier will start to link slalom cuts together, where the objective is to be able to carve on their edge as much as possible. As a slalom skier becomes more advanced they will start to use a slalom course. The course consists of a number of buoys (anchored, floating markers) that form two paths, one for the boat and one for the skier. The boat path is a straight line directly down the center of the course and the skier path is dictated by an oscillating series of buoys on either side of the boat path. As the boat travels down the center of the course the objective for the skier is to enter through a set of entrance gates, and then execute a series of left and right turns (three of each) while traveling on the outside of the buoys before exiting through a set of exit gates. The dimensions of the slalom course are standardized, however, the course can be made more difficult by increasing boat speed and decreasing rope length, thus making it harder for the skier to reach the buoys.

One activity, which all levels of slalom skiers need to be proficient in, is a deep water start. This is when the skier is pulled by the boat, from a rest position while sitting in the water, until they have planed on top of the water and begin their run. During this activity some of the highest rope loads are encountered and higher rope loads equate to more pulling force that your body must resist. Therefore, if repeated several times during a skiing session deep water starts can be very taxing on the human body.

Like the majority of sports, the objective of skiers during both of the previously described activities is to maximize performance in the most energy efficient way possible. For a
deep water start a good performance is easily quantified by successfully getting up out of
the water and to do this in the most energy efficient way would be to minimize the rope
load required. While skiing a slalom course, one measure of performance would be how
many turns the skier was successful in completing it on the outside of the buoy. The
parameters that would have an effect on success rate in the slalom course are velocity,
rope load, acceleration and ski orientation.

Product development within the water skiing industry is mainly driven by the desire to
increase performance. For beginners, this could be as simple as designing a product that
is more stable for them to use and easier to learn the basic skills. For intermediate skiers,
this could include designing a product that allowed them to best transition into slalom
skiing and learning how make a good slalom cut. Finally for advanced skiers, it would
include designing a ski that allowed them to maximize their performance during the
advanced slalom skiing activities previously described.

Over the past 30 years, water ski manufacturers have increased ski design performance
through basic ski shape modifications and the use of different manufacturing materials.
However, the design of slalom skis has not progressed at a rate that would be expected
given the level of recreational and competitive participation. Furthermore, the industry
has received little attention in research literature.
1.2 Coaching

The Coaching Association of Canada has developed the National Coaching Certification Program. It is a training and certification program for all coaches across over 60 sports. Their model discusses the following five core competencies: valuing, interacting, leading, problem-solving and critical thinking. The core competencies are what is essential for coaches to achieve the following generic coaching outcomes: make ethical decisions, provide support to athletes in training, plan a practice, support the competitive experience, analyse performance, design a sport program and manage a program (Coaching Association of Canadian, n.d.).

Coaches are classified based on three streams: Community Sport, Competition and Instruction. Each stream is further broken down into different contexts, which help identify the different needs of an athlete as their participation changes. For example the Instruction stream has three contexts: Beginners, Intermediate performers and Advanced performers. Beginners will have first been exposed and participated in the sport through a series of lessons and as their skill grows they become Intermediate and Advanced performers. As this happens they typically will phase into requiring specialized instruction to help them develop enhanced skills through tactical development specific to the sport they are participating in (Coaching Association of Canadian, n.d.).

Water Ski and Wakeboard Canada (2011) describe water skiing as being a blend of five fundamental skills: stance, edging, rotation, pressure control and timing and coordination. They outline that a good water skiing coach needs to understand the five fundamental
skills in order to be able to identify when a skier is having a problem and what the cause of the problem is. With a good understanding of what the cause of the problem is they must be able to choose an exercise to correct it. The effectiveness of this type coaching philosophy is dependent on the accuracy of the coach’s analysis. A more accurate and detailed analyse of a skier’s performance will allow the coach to correctly identify what the cause of the problem is and provide a specific solution to correct it. Currently, optical methods are most commonly used by water skiing coaches. They try to visually identify problems and causes, and use the guidelines for the fundamental skills and key teaching points that they have learned through coach training programs. Having quantitative data would increase the accuracy and effectiveness of the current coaching strategy that is most commonly used (Water Ski and Wakeboard Canada, 2011).

1.3 Instrumentation

There are many challenges that present themselves when applying instrumentation to the natural environment of water skiing. Mounting equipment to an athlete who is participating in a highly dynamic sport is always challenging and having to waterproof everything drastically increases the challenge. Likewise, operating electrical equipment in a power boat has its own set of obstacles, being that it is a relatively “noisy” electrical environment.

The advancements in global positioning system (GPS) technology and the development of inertial measurement units (IMUs) have been the most influential in improving the analysis capabilities of highly dynamic sports [Brodie et al., 2008; Waegli et al., 2007a,
They can be implemented to quantify characteristics and events that occur during a dynamic activity. Traditionally these events were qualitatively analyzed using optical methods or by an athlete’s “feel”. The long term outcome from Brodie (2008) and Waegli (2007a, 2007b) is yet to be published but they have demonstrated that having quantitative data will allow for a more accurate and detailed analysis of dynamic events and will be beneficial for product development and coaching techniques.

The implementation of GPS, an IMU and an axial load cell should allow for data collection of the desired performance parameters previously described. Skier and boat GPS modules will be able to provide normalized skier velocity. An IMU located on the water ski will provide ski orientation, acceleration and deceleration and an axial load cell in series with the tow rope will provide rope load. Capturing the performance parameters will allow for improved proved product development, coaching techniques and injury prevention within the water ski industry.

1.4 Methodology

There are several uncontrollable factors that can have an influence on the performance of a water skier and the development of an experimental procedure that would minimize their effect is essential. Human participants were recruited based on their skiing ability, the criteria being that they could comfortable ski two passes of a slalom course four times throughout each test day. Six subjects, with an advanced skill level, were selected and
completed their test runs throughout three experimental test days during the summer months of 2010.

The goal of each of the test days was to mimic skiing conditions that would present themselves during everyday skiing, while implementing a controlled and structured experimental procedure. It was important to provide test conditions that were relatively equal for all of the human participants, which makes a cross comparison between them viable.

The first step in providing a more controlled environment is to minimize the effect of the two main factors, which are uncontrollable by the athlete: weather and boat control. In addition it was vital to develop an experimental procedure that would have a high number of repeatable events, given the available resources, while minimizing the effect of fatigue. To accomplish this, a slalom course was used and each skier was required to perform a distinct sequence of events while using four different skis in a randomized order throughout each experimental test day. Highly experienced boat drivers and an automatic speed control system were used to provide the best boat control possible.

The goal of this study was to combine the instrumentation and methodology to collect data during the deep water start and cutting portion a slalom run. Initially only turns completed on the outside of a buoy were going to be used for analysis, however, the difficulty that the subjects would have while skiing on equipment they were unfamiliar with was underestimated. Therefore the criteria for a “good” cut was expanded to include
those that were not completed on the outside of a buoy but still were the proper representation of an advanced slalom cut. The number of completed turns around the buoys was instead used as a quantitative measure of performance. Skier velocity, acceleration and deceleration as well as ski orientation were the other performance parameters of interest. In combination they could be used to assess the success of a skier during the cutting portion of their run. Once again the objective would be to maximize their performance while minimizing rope load and thus being more efficient.

Four skis were chosen for analysis in this study and each skier completed a minimum of one test run on each of the ski designs. Skis were chosen based on their design, with the objective being to have a spread of data that was able to identify any differences in performance. Quantitative data collected was used to analyse the difference in performance between the four skis as well as skiers. The purpose of the study was to fill a void found in research literature and provide quantitative data for advanced slalom skiers. The subsequent analysis procedure would provide an improved method for the assessment of skier performance. Having a benchmark for a skier’s performance allows for that data to be compared to another skier, the same skier on different equipment or the same skier while implementing a different technique. Therefore, this type of improved analysis will allow for advanced product development and coaching techniques in the water ski industry.
1.5 Thesis outline

Chapter 2 will provide the necessary background to provide the context of this research. It will be presented as a literature review.

The results from the previously described instrumentation and methodology will be presented in three papers that have been placed in three separate chapters. The papers will all be submitted to the Journal of Sports Engineering and Technology. The first paper is titled “Methods and Instrumentation used for Biomechanical Analysis of Slalom Water Skiing”. It provides details and design choices for the instrumentation and the methodology that was implemented to provide a strong data set. In addition, it provides some sample data, discusses the applications of the data and some the issues that were encountered. The intention is for this paper to be submitted as a technical note.

The second paper is titled “Water Skiing Biomechanics a study of Advanced Skiers”. It provides detailed results from the GPS and axial load cell, including the overall results of each skier and ski. The statistical significance and applications of the results will also be discussed.

The third paper is titled “Biomechanical Analysis of Slalom Water Skiing: an in-depth look at a slalom cut and skier dynamics”. It will give a unique look at the different phases of a slalom cut and provide the detailed results from the IMU, including the overall results from each skier and ski. The statistical significance and application of the results will also be discussed.
The final chapter will provide an overall conclusion of the study and provide details of future considerations. It will be followed by a master list of references for all of the papers.
Chapter 2: Literature Review
2.1 Literature Review

Sports technology research spans from the development of new sport techniques and products for elite competitive athletes, to recreational athletes. Amongst these athletes the motive for research can be used to enhance casual participation, and training for advanced competition. The products that can be improved by sports technology include equipment, apparel and even facilities [Bruggemann, 2009].

Advancements in the material being used to manufacture sporting equipment has generally made equipment stronger and lighter. In some cases it is desired to have a material that is more rigid, like a high-performance bicycle, and in other cases it is desired to have a strong flexible material, like a high-performance hockey stick. In both scenarios the material selection minimizes the amount of energy that is lost while participating, and consequently improves performance [Bruggemann, 2009].

Beyond raw material selection, the emergence of nanotechnology and smart materials have also improved the performance of sporting equipment. Nanotubes can be used to produce an ultra lightweight material with high strength characteristics. Improved manufacturing techniques have allowed for equipment to be made from a nanotube based material. Smart materials will have one or more property that changes due to a secondary stimulation. This can include stress, temperature, moisture, pH and electric or magnetic fields. In the example of piezoelectric materials not only does a stress generate a voltage, but if a voltage is induced it will produce stress within the material. Therefore, this type
of material can be used as a force measurement feedback or it can be manipulated by an input voltage for unique applications [Bruggemann, 2009].

Running shoes are a common piece of apparel for several sports and it has been suggested that running related injuries are due to foot pronation and impact force. Shoe design and manufacturing materials have been developed to reduce the effect of the previously mentioned causes of injury. The classical way to reduce impact force is through the use of air pads, capsul gels and materials such as ethylene vinyl acetate and different densities of polyurethane. Advancements in technology have led to the design of an “intelligent” shoe. It allows for automatic adjustments to be made to the stiffness of the shoe’s sole to adapt to the specific surface they are being used on. The system is controlled by a microprocessor which takes force inputs to determine how the cushioning needs to be adjusted and does so through a motor-driven cable system [Bruggemann, 2009].

Development of the swift-pin cycling suit for cycling is another example of sports technology being used to improve the performance of sports apparel. The suit has been designed to reduce pressure drag or friction drag. The type of drag that exist depends on the different body segment shapes and corresponding different flow patterns over the athlete’s body. Technology was used to analyse flow in a wind tunnel to determine the best material texture that could be strategically placed on different body segments to control the boundary layer. In addition to reducing drag, ventilation was maximized by panels of fine mesh, placed in areas of separated flow [Bruggemann, 2009].
One of the major advancements in athletic facilities is artificial turf. The main goal of artificial turf is to replicate natural turf as accurately as possible. Artificial turf consists of the following components: base layer, synthetic turf, silica sand and infill granules. The choice of material used for each of the components is essential for the turf’s ability to have characteristics similar to natural turf and preserve these characteristics for several years. Technical development of materials over time has allowed for artificial turf to be more acceptable by athletes as an alternative to natural turf. Fibers of the synthetic component mainly consist of polypropylene, polyethylene or a combination of both. Infill granules are most frequently made from rubber or thermoplastic elastomers. The rubber granules are sometimes produced from recycled tires or even recycled tire granules coated in polyurethane [Bruggemann, 2009].

Advancements in instrumentation have improved measuring capabilities which has led to improved analysis of dynamic movements. In the global environment the most popular example of this is using the global positioning system (GPS) to track the movement of an object over land [Meyer, 2002; Zang et al., 2004]. Civilian grad GPS is often criticized for its global position accuracy, which can be up to ±20 m [Meyer, 2002]. This has led researchers to develop systems that combine either multiple GPS units or a GPS unit and other sensors to improve the accuracy of trajectory data [Brodie, Walmsley, & Page, 2008; Meyer, 2002; Waegli, & Skaloud 2007a, 2007b; Waegli, Meyer, Ducret, Skaloud,
& Pesty, n.d.; Zang et al., 2004]. Although GPS does not have high accuracies for position data it does provide good velocity data [Meyer, 2002; Zang et al., 2004].

In the local environment, inertial measurement systems and optical three dimensional (3D) motion analysis systems are used for motion tracking. Optical systems use a number of cameras to record the motion of sensors attached to a subject. With the sensors strategically placed on body segments it allows for the 3D animation of the human body during dynamic activities. Acquiring data about the orientation of an athlete’s body during a specific activity can be used to analyse differences in athlete technique. Limb segment orientation can be combined with force measurements to provide the necessary data for a detailed biomechanical analysis that can be used for rehabilitation purposes and injury prevention [Bruggemann, 2009].

Inertial measurement systems typically implement accelerometers and gyroscopes to determine angular orientation. Orientation is often determined by the integration of the output from the two sensor, using a fusion algorithm. The instrumentation system can not only provide orientation but the raw acceleration and angular rate data from its components [Bachman, Yun, McKinney, McGhee, & Zyda, 2003; Bruggemann, 2009; Luinge, & Veltink, 2005]. Limb segments instrumented with an inertial measurement system can provide information about the orientation and motion of each segment which can be used to generate a similar 3D animation of the human body as the previously mentioned optical systems [Bachman, Yun, McKinney, McGhee, & Zyda, 2003; Bruggemann, 2009; Luinge, & Veltink, 2005]. In addition, the combination of an inertial
measurement system and GPS can be used to provide accurate global trajectory, making this type of instrumentation system applicable in collecting motion data for activities that take place over a long distance [Brodie, Walmsley, & Page, 2008; Waegli, & Skaloud 2007a, 2007b; Waegli, Meyer, Ducret, Skaloud, & Pesty, n.d.].

Despite the international growth of slalom water skiing, it has received little attention in literature. The few studies that do exist lack a strong set of experimental data and in most cases there is no evidence of quantitative results. One author was able to formalize a description of the instrumentation and calculations that could be used to measure several performance parameters. However, there were little experimental results provided to support the validity of the methodology [Macken, 1997]. Another author was successful in designing a simulation of the human kinetics, including joint angles, during a few basic water skiing activities. The validation of the simulation was confined to anthropometric boundaries and basic expectations of how the body reacts during the real activity. Therefore, they too were unable to provide quantitative experimental data for their analysis [Silverberg, & Gardner, 1992]. The most relevant research found in literature is that of Runciman (2011) who was successful in developing a set of instrumentation and methodology that could be used to collect rope load and skier velocity during a set of water skiing activities [Runciman, 2011]. Although the author was able to produce quantitative data, the experimental procedure lacked structure that would minimize the uncontrollable factors that present themselves. For example, a randomized sequence of events was not implemented to minimize the effect of wind and fatigue, and location on the lake where the events were occure was not kept consistent. Furthermore, the
The challenges that present themselves in the natural environment of water skiing have made it difficult to implement an instrumentation system that will provide experimental data [Runciman, 2011]. Outside of waterskiing, technology has been used to provide quantitative data for another highly dynamic sport, alpine skiing [Brodie, Walmsley, & Page, 2008; Waegli, & Skaloud 2007a, 2007b; Waegli, Meyer, Ducret, Skaloud, & Pesty, n.d.].

The first alpine skiing study [Brodie et al., 2008] was successful in fusing data from GPS, IMU, video and an RS-Scan insole system, which allowed them to collect data for alpine ski racing through the entire ten gate slalom course. One of their major successes was implementing an algorithm that fused IMU and GPS data to increase the accuracy of their position data from 50% of measurements being ±5m from the true value, to a maximum error of 1.5m and an increase in orientation error from 20° to less than 5°. The continuous trajectory data from the algorithm was used to calculate race times with respect to a stationary position, a race gate. Race gates were digitized using a GPS mapping system and therefore they could calculate when the athlete passes the respective gate. This allowed for more frequently recorded split times which was beneficial when analyzing a racer’s run [Brodie et al., 2008].
Brodie et al.’s (2008) instrumentation system used twelve IMUs on several limbs of the body in combination with a GPS/IMU system on the helmet to create a 3D animation of the ski racer. This can be used in combination with split times at each gate to not only determine which racer is in the lead but also possible diagnose the technique that is allowing one racer to lead the other. They also were able to model the athlete’s center of mass (COM) trajectory throughout the entire run. From this, they were able to calculate the resultant force acting on the athlete’s COM by twice differentiating the trajectory to find acceleration and multiplying the result by the athlete’s mass. A plot of the COM trajectory and resultant force provided information about when forces were causing acceleration or deceleration, with respect to timing of the turn. When a pressure measurement system was introduced into the system and was used to find the foot loading ratio they were able to measure the ground reaction forces through inverse dynamics. Furthermore, the power that the respective forces were generating can be found from taking the dot product of the force and COM velocity vectors. This enabled the authors to analyze when the athlete’s technique was creating positive power, which was desired [Brodie et al., 2008].

The second alpine ski study [Waegli et al., 2007a, 2007b] integrated an IMU with GPS to not only derive accurate position and orientation data but also fill in gaps in position data during GPS outages of up to 10s. They employed a second method for determining split times of a skier that used a skier’s path as a reference, not a stationary gate. They achieved this by creating planes perpendicular to the reference skier’s trajectory and calculating when a second skier’s trajectory path would intersect the reference. This
allowed them to plot a velocity versus time graph that clearly represents through what sections of the course one athlete is faster than the other [Waegli et al., 2007a, 2007b]. In a later article they went one step further to equip each ski with a sensor system that could be used in combination with a digital terrain model to calculate the orientation of each ski with respect to the slope. This data was used to analyse the roll, heading and skidding profiles with respect to time, during the ski run [Waegli, Meyer, Ducret, Skaloud, & Pesty].

The two previously described studies were able to implement a sensor system that allowed them to investigate the kinematics occurring in alpine skiing. In the alpine skiing environment they were able to equip their human participants by directly attaching sensors to the subjects body and skiing equipment. Furthermore, they both used backpacks to hold additional electrical equipment. The impact that this research will have on alpine skiing is yet to be seen, but in the long run it may potentially revolutionize coaching and product design by providing quantitative data for skiing performance. This data can be used to increase a coaches ability to analyse skier performance and provide addition tools to asses and correct performance problems [Brodie et al., 2008; Waegli et al., 2007a, 2007b].

Improvements in sports technology has helped develop the sports it has been applied to. Other sports, such as alpine skiing and water skiing, have significant challenges that have prevented the extensive collection of quantitative data. The long term results for alpine skiing, due to the recent availability of quantitative performance data, is yet to be
published. However, it has been suggested that the data is the first step to improvements within the sport. There is little evidence of quantitative data for water skiing available in the research literature, and this has most likely limited development within the water skiing industry.

This study was developed to overcome the challenges of applying an IMU/GPS instrumentation system in the natural environment of water skiing, and to provide quantitative data to analyse water skiing’s complex kinematics. It expanded on the work of Runciman (2011) to include a more structured experimental procedure that provided qualitative data for the performance of six advanced slalom skiers on four different ski designs. The goal was to be able to identify different performance achievements on the different ski designs as well as identify different performance achievements between the skiers. Advancements in sports technology will allow for the implementation of an improved instrumentation system that will be able to produce quantitative data that will fill the void found in literature. This type of data set will act as a tool for improved analysis of skier performance and being able to assess skier performance in more detail than previously possible will act as the primary step towards advancements in product design and coaching techniques.
Chapter 3: Methods and Instrumentation used for Biomechanical Analysis of Slalom Water Skiing
Methods and Instrumentation used for Biomechanical Analysis of Slalom Water Skiing

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Abstract

There are many challenges when mounting instrumentation to athletes during highly dynamic sports and the natural environment of water skiing increases the challenge. An instrumentation system and methodology have been designed and implemented to collect quantitative data for slalom water skiing. The performance parameters of interest were: skier velocity, ski acceleration, ski deceleration, ski roll and rope load. The following four sensors were used to collect data to calculate the parameters: boat GPS unit, skier GPS unit, axial load transducer and ski IMU. Six human participants were recruited to ski on four different ski designs. The quantitative data demonstrates how this instrumentation system and methodology overcame the challenges that present themselves in this environment. Furthermore, it is discussed how the data could be used for advanced product design and coaching techniques.
1 Introduction and Background

Slalom water skiing is an increasingly popular recreational and competitive sport with approximately 10 million North American participants annually [SGMA, 2003]. This level of participation is impressive considering that it requires specific equipment and a unique environment that has given it the reputation of being a luxury sport. In 1995 slalom skiing was introduced to the Pan American Games, providing evidence that despite its lack of availability, it has grown to be a popular international sport [“Pan American Games”, 2011].

In contrast to an increasing level of international participation, water skiing has limited studies found in the research literature. Advancements in technology within the biomechanics industry has allowed for improved methods for analyzing other highly dynamic sports. In many cases quantitative results have been used to replace the traditional optical methods. Having performance data throughout a specific activity provides a more accurate and detailed assessment tool than observing an end result. These data sets can be used to compare the performance of two athletes or one athlete while using different equipment or while implementing a different technique. Therefore, this type of comparison can be used as a tool for improved coaching capabilities and product development.

There are many challenges when mounting instrumentation and recording data for highly dynamic sports and the natural environment of water skiing has additional obstacles. This
is most likely the main reason why the few studies that have been done were lacking experimental data to support their research. For example, one author described equipment that could be used to record a few of the parameters that would evaluate the performance of a water skier. However, there was limited sample data or concrete conclusions of the results [Macken, 1997]. Another author was able to develop a successful simulation of the mechanics of water skiing motion during a few typical water skiing activities. Once again there were limited experimental results to support the simulation results and boundary conditions [Silverberg, & Gardner, 1992].

Like most highly dynamic sports there are many evaluation parameters that can be used to gauge a skier’s performance. The utilization of a slalom course is a simple way to evaluate skier success where the difficulty of the course can be increased by increasing boat velocity and decreasing rope length. The performance parameters that would have an effect on the success rate of a skier in the course would be: skier velocity and acceleration, ski orientation and rope load.

Technological advancements have made the instrumentation used to quantify these parameters more accessible and applicable for water skiing research. Previous work by Runciman (2011) was able to demonstrate that the global positioning system (GPS) could be used to measure boat and skier velocity. The author was also successful in implementing a basic axial load transducer to measure rope load [Runciman, 2011]. There are several electrical sensors that could be used to measure ski orientation and acceleration independently but the recent development of inertial measurement units
(IMUs) has allowed for the implementation of one sensor that will be able to measure orientation, acceleration and angular rate.

An inertial measurement unit (IMU) is a versatile electrical sensor that combines the output from accelerometers, gyroscopes and magnetometers to give the three-dimensional (3D) orientation of an object. Thus, it is classified as a six degree of freedom motion sensor. There are different algorithms and mathematical relationships that have been reported in literature that will fuse the sensor signals together in order to achieve the most accurate orientation estimation. Complementary and Kalman filters are two examples that have been used in the research literature [Bachman, 2000; Luinge, & Veltink, 2005]. The algorithm used is highly dependent on the type of components used and in what combination the manufacturer has deemed necessary to achieve their desired output. Thus the mathematical relationships and fusion algorithms will vary depending in the IMU design. The applications of orientation data is widespread amongst several industries, including: biomechanics, robotics, aerospace, underwater vehicles, automotive and virtual reality [Bachman, 2000; Bachman, Yun, McKinney, McGhee, & Zyda, 2003; Brodie, Walmsley, & Page, 2008; Luinge, & Veltink, 2005; Waegli, & Skaloud 2007a, 2007b].

GPS is a well known technology that has been widely used to track the position and speed of an object over land. It often is criticized for the accuracy of the position data, which can be up to ±20 m, and low update rates, which are typically in range of 1-5 Hz [Meyer, 2002]. The increasing availability of higher update rates is making it more
applicable to dynamic sports [Brodie, Walmsley, & Page, 2008; Waegli, & Skaloud 2007a, 2007b; Waegli, Meyer, Ducret, Skaloud, & Pesty, n.d.]. An important consideration when GPS is being used to measure velocity is that the update rate is high enough that it can detect the key velocity characteristics. Application of the Nyquist theorem would lead to the conclusion that to avoid aliasing we must sample at rate higher than twice the frequency of the velocity characteristic with the highest frequency [Broesch, Stranneby, & Walker, 2009].

Load cells have a wide range of sizes and configurations that have been used in many applications. They use sensors to detect the deformation of a material and through a calibration process it can be determined what forces caused the deformations. The measurement sensor and configuration as well as fabrication material used to construct an axial load transducer are critical in the system sensitivity and robustness [Runciman, & Nicol, 1993].

This paper will provide details of the instrumentation and methods used to collect quantitative data from six advanced slalom skiers, including design choices and experimental criteria. It will also provide a sample of the typical results produced from the sensors and a brief discussion about how the results could be used for biomechanical analysis and water ski product design.
2 Methods

The natural environment surrounding water skiing provided many challenges when designing an instrumentation system and methodology. The uncontrollable factors such as weather, boat operation and fatigue were minimized with a highly structured experimental procedure. Instrumentation design choices were made considering that any instrument that was to be mounted to the ski or skier needed to be waterproofed, the data needed to be manipulated for analysis after each test day, the data needed to be collected by a host computer and instruments needed to be able to withstand a harsh environment.

Wind was monitored throughout each test day using a temporary data collection station. The station was located on a dock at a location that was exposed to the relatively same wind as where the subjects were skiing. Data was collected from an anemometer (#40C, NRG Systems Inc, Hinesburg, Vermont), located approximately six feet above the surface of the dock, by a data logger (SynphoniePLUS, NRG Systems Inc, Hinesburg, Vermont). Wind effects were negligible because subjects were required to ski one run into the wind and the other with the wind and the results from each test run were averaged.

Determining what type of IMU to apply to a specific application is very important and there are several commercial options available on the market. Each type has its own set of pros and cons that need to be incorporated into the decision process. For this study the most desirable solution was a self contained product that required a minimal amount of signal conditioning after the signal was received from the unit.
The product chosen that best met the requirements for this research was the Microstrain 3DM-GX2 (Microstrain, Inc., Williston, Vermont). It is composed of an array of magnetometers, gyroscopes and accelerometers that allows it to output a wide range of inertial measurements. The internal signal conditioning allows the sensor to be accurate and durable in a wide range of experimental environments and the commercial software provided with the sensor allows for easy onsite parameter programming. The unit was programmed to output 3D-acceleration, 3D-angular rate and an orientation matrix at a rate of 20 Hz. This resulted in an effective data rate of 12.6 kbps.

The IMU unit communicated with the host computer via a custom fabricated 2 GHz RF transceiver system. The system used four transceiver modules (nRF2401, Nordic Semiconductor ASA, Tiller, Norway), two on each breakout board, that were controlled by a microcontroller. The microcontroller implemented a custom control program and the two breakout boards were custom designed, by Groendyk, N. On each board, one transceiver was designated as the receiver and the other the transmitter, allowing the microcontroller to receive and send data simultaneously. This arrangement increased the efficiency of the system and allowed for the transmission of data at a high and sustained throughput rate. One transceiver system was connected directly to the IMU unit on the ski using the RS232 protocol, and the other was connected to the computer in the boat via a Universal Serial Bus (USB) port.
The ski based IMU and transceiver system was housed in a plastic box and mounted to the water ski in front of the front binding. A custom fabricated aluminum plate was bolted to the ski using the same footprint as the front binding and fabric straps were used to secure the IMU box to the plate. The IMU box was wrapped in plastic and placed in a water resistant bag for waterproofing. The setup can be seen in Figure 1. Weights of the four skis and IMU box were recorded, however details of the different ski designs is not within the scope of this paper.

![Figure 1](image)

Figure 1: a) IMU system in its housing strapped to the front of one of the skis. b) IMU and its transceiver system mounted in plastic box

Skier velocity and boat velocity were recorded using similar methods to the previous work of Runciman, J. [Runciman, 2011]. The author used two GPS units, one located on the test subject and the other on the boat. When evaluating the previous work it was determined that the boat unit could remain the same but an upgrade to the subject unit was desirable to capture more of the skier velocity profile.

GPS time, boat velocity and boat location were collected from the GPS unit in the boat at 1 Hz. The boat unit was an off the shelf product (BG-331RGTGT, Mighty GPS, Toronto,
ON) that did not require any modifications and it communicated with the computer directly via USB port. GPS time, skier velocity and skier location were collected from the skier unit at 5 Hz. The skier GPS unit was constructed from a GPS module (LS20032, LOCOSYS Technology Inc, Xizhi City, Taiwan) and custom fabricated breakout board. The breakout board was designed to power the unit with two 9 V batteries and transmit the GPS signal from the module to the computer via an RF transceiver system. The RF system consisted of two transceivers (ER900TRS-02, Low Power Radios Solutions Ltd, Witney, England), one connected to the GPS module and the other connected to the computer via USB port. The breakout board also allowed for direct connection to the GPS module for programming. The GPS unit on the skier was wrapped in plastic and mounted between the outer shell and foam lining of the skier’s helmet, as seen in Figure 2 (Cascade Helmets, Liverpool, NY).

Figure 2: GPS unit wrapped in plastic and mounted in the helmet

The environment during the test days requires a load cell that is minimally affected by changes in temperature and can easily be made waterproof. It was constructed with four strain gauges (N11-Fa-10-120-11, Shinowa Corporation, Tokyo, Japan) arranged in a full
Wheatstone bridge on a piece of aluminum tubing. The signal from the gauges was amplified by a custom fabricated strain gauge amplifier (DiCaprio and Thomason 1989), before it was converted to a digital signal using an A/D card (USB-6211, National Instruments Corporation, Austin, TX). The amplifier was powered by a power supply (E3630A, Agilent Technologies Canada Inc, Mississauga, Canada) that ran off a 300W power inverter (Zantrex, Elkhart, IA) connected to a 12 V deep cycle marine battery (Nautilus No. 10-279904, Canadian Tire Corporation, Toronto, Canada). The output signal from the A/D card was sent to the computer directly via USB port. The amplifier allowed for DC offset, excitation voltage and balance adjustments to the system. The excitation voltage was set to 5 V, which allowed for the maximum sensitivity of the system without overheating the gauges, causing temperature artifacts.

The voltage readings from the load cell were converted to Newtons with a calibration equation. A unique equation was derived for each of the test days using a calibration procedure that included static load measurements using known weights. A data file was produced while a series of weights were hung from the load cell, allowing for the production of a Force vs Voltage plot which could be fit with a linear model (Appendix A).

The four instruments previously described had individual output data streams that needed to be linked in time. This allowed for a cross reference type of analysis that could indicate the skier speed, ski orientation and rope load at a specific point in time during an experimental ski run. The best way to achieve a time link in this scenario was to create a
single data collection program that would parse all the incoming data streams and write them to a data file, where each row of the file represented a single time frame. The data output from the four sensors were received as digital signals and they were converted to an analogue output via the data collection program. The program was created using Labview (Labview 8.2, National Instruments Corporation, Austin TX) and ran at 20Hz. The program allowed for individual communication baud rate settings that needed to be matched with the baud rate of the particular instrument. The two GPS units were programmed using product software before being connected to the data collection program. Therefore, when they had power they were constantly sending data to the computer but the data was not being received and parsed until the data collection program was initiated. The IMU required commands to be sent to the unit for proper operation and therefore the data collection program required an interface that was capable of this.

This study was reviewed and received ethics approval for its human participation and written survey components by the University of Guelph Ethics Committee. A sample of the survey can be found in Appendix B. There were six human participants that were recruited based on their skiing ability. They were required to ski two passes of a slalom course on four different slalom skis throughout the test day. This made our subject pool to be advanced slalom skiers. In an ideal situation the number of repetitions of each activity would have been calculated using statistical power analysis, where statistical power would represent our ability to detect an effect, if it does exist. A target power value would have been chosen and the number of observations required to achieve that value could be calculated [Park, 2008a]. Given our resources a prospective calculation
was not practical and the number of repetitions for the desired activities was maximized through a controlled, repetitive experimental procedure that used a slalom course.

One experimental ski run consisted of mounting the two subject sensors, IMU and GPS on the subject and ski then starting the data collection program with the slalom ski in an assigned position on land. The boat then took the subject and ski to one end of the slalom course where they did a deep water start, followed by two passes of the slalom course. One pass of the slalom course consisted of an entrance cut, followed by six slalom cuts, three lefts and three rights (see Figure 3). The purpose of starting the data collection with the ski in an assigned position prior to leaving land was to have a reference point for the IMU sensor after it was transferred from one ski to the next. The order that each subject skied on the skis was randomized in order to reduce the effect of fatigue and weather. To further help minimize the variables that would influence the results, all of the ski runs were done on the same slalom course with the same rope length, 17.9 m. In addition, boat speed was controlled using an automatic control system that was set to 51.5 km/h for all of the ski runs. This is a common boat velocity for slalom water skiing and it was chosen by the human participants.
Figure 3 - Diagram of slalom course including entrance gates (x), skier path and buoys 1–6 (o) and sample dimensions [“International Waterski & Wakeboard”, 2010].

During each of the ski runs observational recordings were made about each of the activities. They were used during the data processing after the test runs to determine what activities had taken place. The most important pieces of information were the number of deep water start attempts it took to get up, the number of turns completed and how many turns the subject successfully went around the buoy. In some instances the subject may have performed a turn but it was deemed to be inadequate in comparison to the subject’s other turns. This criterion was only used in extreme cases, for example the subject may
have almost fallen but recovered and continued to ski the course. In all cases the written observations were cross referenced with qualitative data before being excluded from the analysis.

The data files were all processed using Microsoft Excel (Microsoft Canada Co, Mississauga, Canada) and the first step was to perform a series of unit conversions. The orientation matrix from the IMU was then used to calculate pitch, roll, and heading. The roll data was used to determine the boundaries of each turn such that a turn started and ended when roll was equal to 0°. A left turn occurred when the roll angle was greater than 0° and a right turn when it was less than 0°. The data files could then be broken down into left and right turns and resultant peak rope load, skier velocity, ski roll, ski acceleration and ski deceleration could be calculated. It was also of interest to calculate the integral of the respective parameter profiles to investigate the cumulative result over a period of time. The acceleration data was filtered using a moving average, where five data points were used as the averaging window.

After the previously mentioned performance parameters were calculated a generalized linear mixed-model was employed for statistical analysis. When testing the performance of the skis, factors included in the model were ski turn and skier as well as their interactions. The assumptions of the ANOVA were assessed by comprehensive residual analyses. Three common numerical normality tests were performed, a Shapro-Wilk test, a Kolmogorov-Smirnov test, a Cramer-von Mises test, and an Anderson-Darling test [Park, 2008b]. Residuals were plotted against predicted values and explanatory variables to look
for patterns in the data that suggest outliers, unequal variance or other problems. If residual analyses suggested a need for data transformation or data was presented as a percent, analyses were done on a logit or log scale. If the overall f test was significant a tukey test was applied. (SAS Institute Inc. 2004. SAS OnlineDOC (R) 9.1.3. Cary, NC: SAS Institute Inc)

3 Results

The mass of the four skis ranged from 3.81 to 4.63 kg and the mass of the whole IMU setup was 0.87 kg. The impact of additional weight was found to be negligible.

Figure 4, Figure 5 and Figure 6 are examples of the typical streams of data that were produced from one ski run. All three of the figures were taken from the same run and the data from when the collection program was started on the dock was excluded for clarity. Therefore, 0s in the figures is relative and not when the program was started. The major activities of interest can be easily identified from the figures. The first large peak in rope load indicates the deep water start and the relatively large force that is required to pull a skier out of the water (2000 N at 20 s). During this time the IMU is submerged under water and therefore the RF signal is not being received. As the boat approaches its target speed and the skier begins to plane on top of the water, the rope load stabilizes to its nominal value that is required to pull the subject across the water and the IMU signal begins reception. The next smaller peak in rope load, positive roll peak and acceleration peaks at 35 s indicate the subject’s setup cut before entering the entrance gates of the course. The following series of rope load peaks, skier velocity peaks and oscillating roll
and acceleration peaks represent the subject making their six slalom cuts through the
course. After they exit the course, rope load stabilizes again while the boat rotates 180°,
and the activities are repeated during the second pass of the course. The 180° rotation can
be identified in Figure 5 from the heading data stream.

Figure 4: Example rope load, skier velocity and boat velocity data for one test run. Major activities
include: start up (SU), entrance cut (EC), slalom turns (ST) and boat turn around (BTA).
Figure 5: Example ski pitch, roll and heading data for one test run. Major activities include: start up (SU), entrance cut (EC), slalom turns (ST) and boat turn around (BTA).

Figure 6: Example ski acceleration/deceleration data for one test run. Major activities include: start up (SU), entrance cut (EC), slalom turns (ST) and boat turn around (BTA).

Figure 7 is an example of the signal loss issues that were experienced with the IMU RF transceiver system. When the signal is lost the data collection program repeats the last received data packet and therefore it is represented in the figure as a horizontal line. Bad reception was only experienced on a small percentage of the test runs (approximately
8%) and the intermittent loss was a more frequent trend found on the first test day (approximately 15%). Signal loss was rectified by making an adjustment to the transceiver unit on the boat.
Figure 7: Example IMU data signal reception a) good b) bad and c) intermittent. Loss of signal is represented as horizontal lines of repeated data.
4 Discussion

During the experimental runs the IMU enclosure was not found to noticeably interfere with skier performance. Subjects did take notice to the extra weight but with minor adjustments they were still able to perform as expected. Any effect on performance was considered negligible within this study because all skis and skiers were tested under the same conditions.

The structure of the experimental procedure was created to minimize the effect of wind throughout each individual test day and between testing days. It is important to recognize that because the subjects did not all ski on the same day if one day affected performance significantly more than another day, it might affect the ability to compare between the skiers. To alleviate this concern, wind speed and direction were recorded and found to be approximately equivalent between days. In addition, for the subjects that skied over multiple test days there was no noticeable impact of weather on their success rate results. The effect on the analysis between the skis will be negligible because the skis were all used equally over the three test days.

The methodology and instrumentation used in this study were successful in collecting data that could be used to determine skier velocity, ski acceleration/deceleration and rope load. No major modifications needed to be made to the instrumentation during the test days and the only technical issue encountered was the signal loss with the IMU RF transceiver system.
RF communication systems are easily implemented in a wide range of applications, however their signal can easily be interfered with by environmental noise. The 2 GHz units used with the IMU were especially sensitive to environmental noise and given the harsh testing environment there was noticeable signal loss in a few of the test runs. The exact cause of the signal loss was hard to pinpoint but when measures were taken to produce the best signal strength and receiver position the signal loss was significantly reduced. The intermittent signal loss shown in Figure 7-c) occurred when roll was approaching its peak negative value, which could be due to the transmitter momentarily losing “sight” of the receiver. There was no noticeable trend for when the signal was completely being interfered with as seen in Figure 7-b). It was hypothesized that there could be overheating issues with the voltage regulators on the breakout board inside the IMU enclosure. For further troubleshooting a larger aluminum heat sink could be attached to the back of the IMU, increasing its ability to stay cool in this type of environment.

All of the equipment choices were appropriate and the minor issues discussed should be corrected by making adjustments and therefore no replacements are required. The decision to upgrade to a 5Hz skier GPS unit was an appropriate choice. The period of one turn was approximately 3s, which correlates to a frequency of 0.33Hz. The frequency of one turn was determined to be the highest frequency of interest and therefore, Nyquist theorem suggests that a minimum sampling rate 0.66Hz be used. Our sampling rate of 5Hz is approximately 7.6 times the suggested frequency and the frequency used by Runciman (2011) was only 1.5 times the suggest frequency. It is important to note that
Nyquist theorem applies under the assumption of a pure sign wave and although the data has sinusoidal characteristics it is not a pure sign wave. Therefore, even though Nyquist theorem is applied there is still the possibility of aliasing [Broesch, Stranneby & Walker, 2009]. Potential for errors in detecting velocity changes were reduced with the 5Hz skier GPS unit. However, to further reduce the potential for errors it would be desirable to upgrade to a skier GPS unit with a higher update rate. The collection rate of 20Hz used by the other instruments was appropriate for minimizing the potential for detection errors.

This data can be analyzed and applied in multiple ways and sheds light onto the future roll of technology in the water ski industry. For example, the parameter profiles found in Figure 4, Figure 5 and Figure 6 can be used to calculate peak values while cutting. An analysis of average peak values could be used to determine if a specific skier technique, ski design or equipment setup led to a significant different result that any other. The load profile, found in Figure 4, can also be used to calculate peak rope load during a deep water start, which similarly can be used to determine if a specific skier technique, ski design or equipment setup led to a significantly different peak rope load than any other. However the peak rope load does not give an indication of total energy consumed, which can be determined from a more detailed analysis of the load profile with respect to time. This was not covered in the scope of the study. The load profile would be essential for any biomechanical analysis that would combine limb segment orientation to further analyse the force impact on the human body.
The roll profile can be used to determine key turn characteristics, such as when the peak roll occurred during the turn and how consistent each turn shape is. This type of analysis could be used as an indicator for turns that may represent outliers for a “typical” slalom cut, which could help increase skier repeatability. Increasing a skier’s repeatability would be beneficial for optimizing equipment setup and skier technique, where a skier would want to able to repeat maximum performance on every turn. Having a velocity and ski orientation profile is also essential for any detailed fluid dynamic analyses that would be used for advancements in ski design.

The total performance of a slalom skier can be gauged by their success in a slalom course (ie how many buoys they were able to go around). All of the performance parameters previously discussed would have an impact on the skier’s success rate and a complete analysis of the results would include interaction between them. For example it would be of interest to know when the acceleration occurs during the turn and how that relates to the ski orientation and rope load. This would help identify the key mechanisms that are allowing a water skier to have optimal performance and if they change depending on ski design and skier technique.

5 Conclusion

This study demonstrated the instrumentation system and methodology that can be used to record biomechanical performance data while slalom water skiing. Improvements were made on the instrumentation and methodology used by Runciman (2011) in a previous
study. Most significantly the skier GPS unit was upgraded to a module that provided data at 5Hz, a slalom course was used to enforce a more structured series of activities and an IMU sensor was added to the slalom ski to quantify 3-D ski motion.

The typical data streams produced from the instrumentation demonstrate the variety of performance parameters that can be abstracted. The application of the results could include advanced equipment design, equipment setup optimization, skier technique optimization.

Data transmission issues and time constraints were the largest hurdles during the test days. For future data collection sessions it will be essential to resolve the intermittent signal loss with the IMU RF transceiver system. The cost and challenges involved in organizing this study make it crucial for each test day to be used effectively.

6 Acknowledgements

For simplicity, all acknowledgements can be found after the main title page of this thesis.

7 References

For simplicity, a master reference list was used and can be found after Chapter 6.
Chapter 4: Water Skiing Biomechanics a Study of Advanced Skiers
**Water Skiing Biomechanics a Study of Advanced Skiers**

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Key Words: biomechanics, load transducer, GPS, water skiing, slalom, advanced skier

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Abstract

Six advanced slalom skiers were recruited to test four different ski designs over the summer months of 2010. An axial load transducer, boat GPS and skier GPS were used to calculate rope load and skier velocity for the skier during the deep water start and cutting portion of a slalom run. The methodology was designed to reduce the uncontrollable factors that present themselves in the natural environment of slalom water skiing. There was enough statistical evidence to suggest that there was a difference in the average peak rope load produced between the skis. The typical average peak rope load and skier velocity, for an advanced skier, during the cutting portion of a ski run is in the range of 1.41-2.74 times body weight. The instrumentation was unable to provide enough evidence to suggest that there is a difference in the peak skier velocity during cutting or peak rope load during deep water starts. The typical average peak skier velocity while cutting and rope load during a deep water start, for an advanced skier, is in the range of 113.71-135.43 % of boat speed and 1.74-2.74 times body weight. Furthermore, there was enough evidence to suggest that there was a difference in the performance between the skiers. This type of analysis will provide a more detailed performance evaluation than what is currently available for product design and coaching. Therefore, it will improve product design capabilities and coaching techniques.
1 Introduction and Background

Water Skiing is most commonly perceived only as a luxury sport and the number of annual participants is approximately 10 million in North Americans [SGMA, 2003]. Amongst the large number of participants, there is a growing competitive culture that has developed to include international competitions and the introduction of Slalom Skiing into the Pan Am Games in 1995 [“Pan American Games”, 2011].

In recent years product development has mainly been driven by companies wanting to produce the product that allowed for maximum skier performance in a competition. In addition to designing skis that would produce the highest level of performance, ski manufacturers have developed products for the full range of skiing ability, including wider profile skis that have been designed for intermediate recreational skiers to reduce the loads on their body.

There are several water skiing based sports that are typically practiced competitively, the one that also most frequently enjoyed at a recreational level is slalom skiing. Slalom skiing is typically practiced by intermediate and advanced skiers and as a skier becomes more advanced they often use a slalom course. Furthermore, as their ability to ski a course increases they may further increase the difficulty of the activity by increasing the boat speed and decreasing the rope length.
Recreational and competitive slalom ski participants often require coaching to further advance their skill level. Water Ski and Wakeboard Canada has developed a results based coaching structure that uses a set of techniques that will allow a slalom skier to maximize their performance. It is the coach’s responsibility to understand the required skills so that they can evaluate a skier’s performance to assess if there is a problem and what is causing the problem [Water Ski and Wakeboard Canada, 2011]. The most common method for evaluating skier performance is through optical methods. The accuracy and effectiveness of this type of coaching philosophy would be improved if quantitative data could be used as an additional tool to analyse skier performance.

Given the popularity of water skiing there is a surprising lack of related published research. One author of interest described equipment that could be used to record some of the performance parameters that would be useful for the analysis of water skiing, however there was limited sample data or concrete conclusions of the results [Macken, 1997]. Another author was able to develop a simulation of the mechanics of water skiing motion that was shown to be a successful simulation of a few typical water skiing activities. Once again there were limited experimental results to support their findings [Silverberg, & Gardner, 1992]. The most relevant is the previous work of Runciman (2011) who was able to demonstrate the typical rope loads and skier velocities of a group of intermediate skiers during a number of skiing activities [Runciman, 2011]. The quantitative results from this study indicate that there is a wealth of relevant skier performance data that can be collected and analyzed.
There is a lack of quantitative experimental data for advanced water skiers available in the literature. The study by Runciman (2011) focused on intermediate skiers and utilized methods that could be used to collect the desired quantitative results for advanced skiers but lacked a controlled environment that would reduce the variables influencing the results. The purpose of this study was to use a more controlled environment to improve the quality of the data and provide quantitative results for advanced skiers. This data will fill a void found in literature and act as a tool for improved analysis of skier performance, which could be applied to optimize skier technique and ski design. This article will provide details of the methods and equipment used to collect rope load and skier velocity data for six advanced water skiers. It will also discuss how the results could be used to analyze a skier’s performance and initiate a more advanced level of product design and coaching techniques within the water ski industry.

2 Methods

This study was reviewed and received ethics approval for its human participation and written survey components by the University of Guelph Ethics Committee. Six male human participants were recruited based on their ability to meet the required test conditions. Test conditions were as follows, each subject had to be able to ski two passes of a slalom course on four different slalom skis in one test day. These test conditions restricted the classification of the subject pool to be advanced slalom skiers. A summary of the subjects can be seen in Table 1.
Table 1: Summary of human participants used in the study.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Weight (lbs)</th>
<th>Height (cm)</th>
<th>Forward Foot</th>
<th>Years Slalom Skiing at Current Skill Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>41</td>
<td>79.38</td>
<td>177.80</td>
<td>L</td>
<td>More than 20</td>
</tr>
<tr>
<td>12</td>
<td>51</td>
<td>86.18</td>
<td>177.80</td>
<td>R</td>
<td>11-15</td>
</tr>
<tr>
<td>13</td>
<td>28</td>
<td>90.72</td>
<td>190.50</td>
<td>R</td>
<td>11-15</td>
</tr>
<tr>
<td>14</td>
<td>30</td>
<td>81.65</td>
<td>177.80</td>
<td>L</td>
<td>Less than 5</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>75.30</td>
<td>187.96</td>
<td>L</td>
<td>11-15</td>
</tr>
<tr>
<td>16</td>
<td>38</td>
<td>74.39</td>
<td>175.26</td>
<td>R</td>
<td>16-20</td>
</tr>
</tbody>
</table>

The development of both the equipment and methods used in this study were driven by the previous work of Runciman (2011). Data was collected over three test days at Lighthouse Lake Watersport Centre in Ontario, Canada. Each of the test days consisted of the following: all subjects were required to complete a written survey to assess their physical attributes, fitness level and historical participation in the sport, all of the test subjects were required to complete their experimental test runs and then all of the subjects were required to complete another written survey that evaluated the different ski models. Overall, the test subjects were required to participate in a minimum of four experimental test runs, one on each of the ski models. The four different ski models varied in classification from a wide profile performance model through to an advanced tournament model. A brief overview of the ski models can be seen in Table 2, and an typical ski profile can be seen in Figure 1. The most aggressive ski design would be that of Ski D, which has a thin profile and is lightweight. The least aggressive design is Ski C, which has the widest profile with a comparable mass to the other two skis.
Table 2: Summary of ski models used.

<table>
<thead>
<tr>
<th></th>
<th>Ski A</th>
<th>Ski B</th>
<th>Ski C</th>
<th>Ski D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (cm)</td>
<td>170</td>
<td>170</td>
<td>170</td>
<td>170</td>
</tr>
<tr>
<td>Width at Widest Point (cm)</td>
<td>17.28</td>
<td>18.53</td>
<td>20.34</td>
<td>17.26</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>2.81</td>
<td>2.81</td>
<td>2.75</td>
<td>2.00</td>
</tr>
<tr>
<td>Classification</td>
<td>Tournament</td>
<td>Tournament</td>
<td>Performance</td>
<td>Tournament</td>
</tr>
</tbody>
</table>

Figure 1: Example ski profile

Each ski run consisted of: an initialization of the sensors on the dock, a deep water start at one end of the slalom course and two passes of the course without a rest in between. A pass of the slalom course consisted of an entrance cut, where the subject sets-up and enters the course through the entrance gates. This was followed by six additional cuts, three left cuts and three right cuts, around six buoys. Figure 2 shows a diagram of the slalom course and the path the skier would follow. If a subject fell during a run they were required to do a deep water start and restart the pass they fell on. To help minimize the variables that would influence the results, a randomized testing procedure was used that ensured the test subjects skied on each of the skis at different times throughout the test day. In addition, all of the ski runs were done on the same slalom course with the same rope length, 17.9 m. Boat speed was controlled using an automatic control system that was set to 51.5 km/h for all of the experimental test runs.
Figure 2: Diagram of slalom course including entrance gates (x), skier path and buoys 1 – 6 (o) and sample dimensions ["International Waterski & Wakeboard", 2010].

Wind speed and direction can have a significant impact on skiing conditions. In order to keep a record of the changing wind speed throughout each of the testing days a temporary weather station was setup along the lake shore. The location of the weather station was on a dock in an area of the lake such that it was exposed to approximately the same weather conditions as the slalom course. Data was collected, by a data logger (SynphoniePLUS, NRG Systems Inc, Hinesburg, Vermont), from an anemometer that was mounted on a pole approximately 6 ft above the dock surface (#40C, NRG Systems Inc, Hinesburg,
Vermont). An observational recording of the wind direction, relative to the center line of the slalom course, was taken at each of the test days.

For each ski run, data was collected from four sensors, two sensors located on the tow boat and two sensors located on the subject. Data from the four sensors was collected by a laptop (Acer Aspire One ZG5, Acer America Corporation, Mississauga, ON) located on the boat. The two sensors on the subject used independent wireless transmission systems and the two sensors in the boat were connected directly to the Universal Serial Bus (USB) ports of the laptop. Data being received by the laptop was parsed at 20 Hz and saved to file by a custom data collection program (Labview 8.2, National Instruments Corporation, Austin TX). The data output from the four sensors were received as digital signals and they were converted to an analogue output via the data collection program.

For the purpose of this paper only details of one of the sensors located on the subject, a Global Positioning System (GPS) unit located in the subject’s helmet, will be discussed. The GPS unit (LS20032, LOCOSYS Technology Inc, Xizhi City, Taiwan) provided skier velocity, direction and position data at a rate of 5 Hz. It was powered with two 9 V batteries and communicated wirelessly with an RF transceiver system (ER900TRS-02, Low Power Radios Solutions Ltd, Witney, England), where one transceiver was located in the helmet and the other was connected to the laptop via a USB port. The GPS unit and transceiver located in the helmet were wrapped in plastic for waterproofing and placed between the helmet shell and foam lining (Cascade Helmets, Liverpool, NY). Another GPS unit was located in the boat and provided boat velocity, direction and location data.
at a rate of 1 Hz (BG-331RGTGT, Mighty GPS, Toronto, ON) and was connected directly to the laptop through a USB port.

The second sensor located in the boat was a custom fabricated axial transducer that was connected in series with the tow rope and used to measure rope load at a rate of 20 Hz. The transducer was constructed with four strain gauges (N11-Fa-10-120-11, Shinowa Corporation, Tokyo, Japan) mounted in a full Wheatstone bridge on the surface of an aluminum tube. The load transducer was powered and amplified by a custom built strain gauge amplifier (DiCaprio and Thomason 1989). The amplifier was powered by a power supply (E3630A, Agilent Technologies Canada Inc, Mississauga, Canada) that ran off a 300W power inverter (Zantrex, Elkhart, IA) connected to a 12 V deep cycle marine battery (Nautilus No. 10-279904, Canadian Tire Corporation, Toronto, Canada). The output from the amplifier was converted to a digital signal using an A-D converter (USB-6211, National Instruments Corporation, Austin, TX) that was connected to the laptop through a USB port. The voltages readings from the load cell were converted to Newtons using a calibration curve that was created before each test day. The curve was derived using a data file that was created from a series of static load measurements from varying calibration weights.

Data files created for each ski run were used to calculate (Microsoft Excel, Microsoft Canada Co, Mississauga, Canada) two performance parameters of interest, rope load and skier velocity. A resultant peak performance parameter was found for each subject’s: deep water starts, left turns and right turns. The resultants were then used to calculate an
average result for the subjects on each of the skis and an average result for all of the
subjects on each ski for: deep water starts, left turns and right turns. For the results of this
paper the turns were divided into dominant and non-dominant instead of left and right.
This is due to the fact that a skier’s dominant and non-dominant turn depends on what
foot they have in the front binding of their ski and therefore is subject dependent. A right
foot forward skier’s dominant turns are right turns which happen when the skier is on the
left side of the boat and the opposite is true for a left foot forward skier. To allow for a
more accurate cross comparison of the results, rope load and skier velocity were
normalized to subject’s weight and instantaneous boat velocity. Although an automatic
control system was used, normalization of skier velocity to instantaneous boat velocity
will minimize the effect of small fluctuations in boat velocity.

Rope load and skier velocity were analyzed using a generalized linear mixed-model for
statistical significance. When testing the performance of the skis three factors were
included in the model: ski turn, skier as well as their interactions. A comprehensive
residual analysis was used to assess the assumptions of the ANOVA. The normality
assumption was tested using four common tests: Shapiro-Wilk, Kolmogorov-Smirnov,
Cramer-von Mises, and Anderson-Darling [Park, 2008b]. Patterns in the data that suggest
outliers, unequal variance or other problems were determined by plotting residuals
against predicted values and explanatory variables. A logit or log scale was used for the
analysis if there was a need for data transformation or data was presented as a percent. If
the overall f test was significant the final step was to apply a tukey test to determine the
3 Results

The two performance parameters evaluated in this paper are rope load and skier velocity and the three data streams used to evaluate the parameters are: rope load, skier velocity and boat velocity. Figure 3 below, shows the typical set of data points that would be generated during one ski run for the three data streams. As the boat begins to pull the skier for their deep water start there is a dramatic peak in the rope load (2000 N at 20 s), and the skier velocity and boat velocity simultaneously increase to the target boat velocity of 51.5 kph. As the boat and subject approach their target velocity the rope load settles to its straight run force (400N at 30s). The subject’s setup for their entrance cut can be seen as the first peak in rope load after it has settled (1100 N at 34 s) and than the subsequent peaks correspond to the subject approaching buoy 1, buoy 2, etc. The subject reaches the end of the slalom course, where the boat turns 180° and the pattern is repeated (without the deep water start), as the subject skis back through the course in the opposite direction.
Due to the high performance demand of the test conditions not every subject was able to complete twelve cuts in the slalom course on every ski. Furthermore, there were a varying number of turns that the subjects were able to go around the buoys. Table 3 contains a summary of the number of completed turns and number of successful turns for each subject. An observational criterion was used to determine if even though a subject did not go around the buoy they still completed a “good” slalom cut. These cuts were still included in the study and success rate was added as a performance parameter that can be used in the analysis.
Table 3: Summary of completed turns and number of successful turns for each subject

<table>
<thead>
<tr>
<th>Subject</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Turns</td>
<td>106</td>
<td>90</td>
<td>75</td>
<td>45</td>
<td>64</td>
<td>46</td>
</tr>
<tr>
<td># of Successful Turns</td>
<td>94</td>
<td>73</td>
<td>17</td>
<td>26</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>Success Rate (%)</td>
<td>88.7</td>
<td>81.1</td>
<td>22.7</td>
<td>57.8</td>
<td>0</td>
<td>69.6</td>
</tr>
</tbody>
</table>

Maximum rope load during the deep water start portion of each skier’s run on each ski was normalized to body weight (BW) and each skier’s average can be seen in Figure 4. Subject 11 had the highest average, 2.64BW and Subject 15 had the lowest average, 1.92BW. Statistical analysis suggests that at least one of the subjects had a significantly different result than another subject (p<0.0001). The error bars shown in the figure represent the calculated pooled standard error from the statistical analysis.

Figure 4: Summary of skier’s maximum rope load results for deep water starts. The highest average was 2.64BW and lowest average was 1.92BW. There was a significant difference between the skiers (p<0.0001). Error bars represent the pooled standard error.
Figure 5 shows the total average maximum rope load during deep water starts for each ski. Statistical analysis suggests that there was no significant difference between the skis (p=0.0993). Although not statistically significant, Ski D resulted in the highest average peak rope load of 2.41BW, and Ski C resulted in the lowest average peak rope load of 2.16BW. The error bars shown in the figure represent the calculated pooled standard error from the statistical analysis.

![Figure 5: Ski’s overall average peak rope load during deep water starts. The highest average was 2.41BW and lowest average was 2.16BW. There was no significant difference between the skis (p=0.0993). Error bars represent the pooled standard error.](image)
Rope load peaks during the cutting portion of the ski run were also normalized to BW and separated into dominant and non-dominant turns. Statistical analysis suggests that at least one of the subjects had a significantly different result than another subject (p<0.0001). Figure 6 shows each skier’s overall average peak rope load during dominant and non-dominant turns. Subject 11 recorded the highest average for both dominant and non-dominant turns, 2.63 and 2.51BW. Subject 15 recorded the lowest average for both dominant and non-dominant turns, 1.54 and 1.53BW. The error bars shown in the figure represent the calculated upper and lower 95% confidence intervals from the statistical analysis.

Figure 6: Skier’s overall average turn peak rope load for dominant and non-dominant turns. The highest and lowest dominant turn average was 2.63BW and 1.54BW. The highest and lowest non-dominant turn average was 2.51BW and 1.53BW. There was a significant difference between the skiers (p<0.0001). Error bars represent the upper and lower confidence intervals.
Figure 7 shows the overall average rope load during cutting for each of the skis for dominant and non-dominant turns. Statistical analysis suggests that there was a significant difference between the skis ($p=0.0244$). Ski D resulted in the highest average for both dominant and non-dominant turns, 2.15 and 2.05BW. Ski C resulted in the lowest average for both dominant and non-dominant turns, 2.08 and 1.93BW. Furthermore, Ski C had a significantly lower average than Ski D ($p=0.0168$). The error bars shown in the figure represent the calculated upper and lower 95% confidence intervals from the statistical analysis.

Figure 7: Ski’s overall average turn peak rope load for both dominant and non-dominant turns. The highest and lowest dominant turn average was 2.15BW and 2.08BW. The highest and lowest non-dominant turn average was 2.05BW and 1.93BW. There was a significant difference between the skis ($p=0.0244$). Error bars represent the upper and lower confidence intervals.
Peak skier velocity for each turn is represented as a percentage of the instantaneous boat velocity. In this case the turns were not separated into dominant and non-dominant because turn type was found to not have a significant impact (p=0.2437). Statistical analysis suggests that at least one of the subjects had a significantly different result than another subject (p<0.0001). Figure 8 shows each skier’s overall average peak velocity for all the turns. Subject 11 recorded the highest average, 133.88 %, and Subject 15 recorded the lowest average, 118.18 %. The error bars shown in the figure represent the calculated pooled standard error from the statistical analysis.

Figure 8: Skier’s overall average peak skier velocity for all turns. The highest average was 133.88% and lowest average was 118.18%. There was a significant difference between the skiers (p<0.0001). Error bars represent the pooled standard error.
Figure 9 shows each ski’s overall average peak skier velocity during cutting for all turns, because there was no significant difference between dominant and non-dominant (p=0.2460). Statistical analysis also suggests that there was no significant difference between the skis (p=0.9309). Although not statistically significant, Ski D resulted in the highest average, 129.02%, and Ski B resulted in the lowest average, 128.59%. The error bars shown in the figure represent the calculated pooled standard error from the statistical analysis.

The average wind speed during the three test days were 2.37, 3.03 and 0.87 m/s. The wind direction during each of the days was consistent throughout all the days and ran approximately 5-10º off the center line of the course. Wave height was not recorded but it was not considered to have significant impact on any of the test days. The impact of the weather conditions on the results was minimized because when possible the subjects completed one pass into the wind and another pass with the wind.
4 Discussion

There are several variables that impact the performance achieved during a slalom water ski run. To minimize the affect these variables would have on the results of this study: a controlled testing environment was used, the results were normalized for better comparison between subjects and weather was monitored. It was underestimated the effect of asking subjects to use equipment they had never skied on before and it was not possible for them to ski at their normal peak ability. This is clear from Table 3 because it was expected that all skiers would have a 100% success rate. Furthermore, the requirement that each subject ski two complete passes of the slalom course on each ski was removed. Each subject still skied two lengths of the course and completed as many turns as possible. This is why the turn totals are not all multiples of six. The ideal ski run would consist of a deep water start with a low peak rope load followed by two complete passes of the slalom course with high peak skier velocities and low peak rope loads.

The recorded wind speed and direction were relatively similar for all three of the test days. However, it is important to recognize that because the subjects did not all ski on the same day if one day affected performance significantly more than another day, it might affect the ability to compare between the skiers. For the subjects that skied over multiple test days there was no noticeable impact of the different skiing conditions on their success rate results. This indicates that there will be a negligible impact on the results of this study. The effect on the analysis between the skis will also be negligible because the skis were all used equally over the three test days.
Success rate results in Table 3 show that subject 15 was unable to complete and turns on the outside of the buoys during his ski runs. This is an indication that he was not skiing at the same level as the rest of the subjects and as expected had a lower average peak rope load and average peak skier velocity than the other subjects. The subject was still included in the study because the results were considered valuable in demonstrating that it is possible to use quantitative data to support the observation that the subject was skiing at a different level. Furthermore, even though the other subjects appear to be more advanced than subject 15 he was able to achieve the lowest average peak rope load during his deep water starts. This was the first indication that it was not only skiing experience that resulted in the different results but also ski technique.

For deep water starts the main performance parameter of interest is rope load, which indicates how much force was required to pull the skier up out of the water. There are several factors that can influence rope load, some of which were uncontrollable during the test runs. This study allowed for the analysis of two of the controllable factors, skier technique and ski design. Figure 5 indicates that there is not enough evidence to suggest that one of the ski designs has more of an influence on rope load during a deep water start than any other (p=0.0993). Although not statistically significant Figure 5 does show that Ski B and Ski C resulted in the lowest average rope load, which is expected since they have the widest profile. In theory a ski with a wider surface should support a skier better and allow them to water start with lower rope loads. In the same respect Ski D resulted in the highest rope load, which was expected because it has the narrowest profile. The same
trend was seen by Runciman (2011) who reported a lower average peak rope load when intermediate skiers were using a wider profile ski, than when they used a tapered ski.

The deep water start results support the qualitative survey, where the numeric ranking that each subject gave the skis was summed to provide a total number of points for each ski. Ski B and C where ranked best for “rope load pulling on arms during deep water starts”, with a total ranking of 25 and 29 points respectively. Ski A and D were ranked worst, both with a total of 17 points (Appendix C). The limited number of repetitions for this particular activity could be why the statistics were unable to detect a difference. In addition, the way the driver accelerates the boat from a rest position will have an impact on the resultant rope load and could be contributing to larger standard errors.

Figure 4 indicates that there is enough evidence to suggest that one of the subjects is able to achieve a different average rope load during deep water starts than any other (p<0.0001). Since load data was normalized to body weight the main variable that would change between subjects is their technique and therefore this is the main contributor to the difference in rope loads. The goal would be to use a repeatable technique that resulted in the lowest rope load. There was not enough qualitative data collected to determine the specifics about each subject’s technique that were having an impact on the rope load results. It would also be of interest to expand the force results to include an energy depletion analysis. This could be done with the implementation of physiological sensors that would provide information about heart rate and blood pressure during the deep water start [Zang et al., 2004]. A analysis of this nature could be used to determine the optimal
technique for slalom deep water starts that would minimize energy consumption and general body fatigue.

The analysis during the cutting portion of the ski run is much more complicated. Peak rope load and skier velocity are both important performance parameters and there are several more variables that would influence them. In addition to the details given in the Methods section, to help minimize these variables, the results were separated into dominant and non-dominant turns and normalized to BW and boat velocity. Both rope load and skier velocity were used to determine if ski design and skier technique had an effect on the performance parameters. Statistical analysis showed that there is a significant difference in the average peak rope load, during cutting, produced from the skis (p=0.0244). Furthermore, as seen in Figure 7 it was Ski C that had a lower average than Ski D (p=0.0168). This is what would be expected since Ski C had the least aggressive design and Ski D had the most aggressive design. The skiers were expected to be able to ski more aggressively on Ski D, which would in turn generate higher rope loads and a better overall performance. Additionally, a ski with a wider, less aggressive design would ride higher on the water, thus reducing the residence and load on the rope. Ski C quantitative results are supported by the qualitative survey, where it ranked best (27 points) for “Rope load pulling on your arms during slalom run”. Interestingly, Ski D did not rank worst for the same question (26 points), but Ski A did (23 points).

A statistical analysis revealed that for peak skier velocity there was no significant difference between dominant and non-dominant turns when analyzing the skiers and skis.
(p=0.2437 and p=0.246). It was expected that a ski with an aggressive design would result in a higher performance than one with a less aggressive design. Peak skier velocity is one of the performance parameters of interest and therefore it was anticipated that there would be a significant different in the results between skis. It is uncertain why the results showed that there was no difference (p=0.9309). Although not statistically significant, Ski D resulted in the highest average and Ski B resulted in the lowest average. It was expected that Ski D would result in a higher average velocity but it was not expected that Ski B would be less than (or similar to) Ski C. Additionally, Ski B was ranked second highest on the performance questions from the qualitative survey, with 150 points. The Ski D quantitative results did agree with the qualitative survey, where it ranked highest in the performance questions (153 points). It is possible that the GPS unit, which is updating at 5Hz, was not detecting peaks at a high enough resolution to reliably compare the event peaks. In other words, the peak velocity might have occurred within the 200 ms duration that the GPS was not receiving a new signal. When the velocity profiles of the subject’s are examined, knowing that the period of one turn is 3 s, there is insufficient evidence to disregard this as a possibility. This could also help explain why there was no statistical significance between dominant and non-dominant turns.

A more detailed analysis of the variables that would influence rope load and skier velocity needs to be performed to fully understand why some of results are not what was expected. This could include a more detailed analysis of the orientation of the ski in the water, determination of when the peak values were occurring during the turn and video evidence to support that each turn was a “good” cut. The other major area of analysis that
would provide insight into the different performance results would include specifics about the ski designs. This study was not able to determine a significant statistical difference between skier velocities achieved on the different designs however the qualitative feedback from the subject survey clearly indicates that they felt a performance difference. A more detailed analysis including orientation and acceleration of the ski could provide more statistically significant results and allow for conclusions to be drawn in respect to the ski designs. It is also important to consider the fact that GPS module was updating at a lower rate (5Hz) than the axial load transducer (20Hz). This could be why the load transducer did detect difference in performance but the GPS did not.

Statistical analysis indicates that there is enough evidence to suggest that one of the subjects is able to achieve a different average peak rope load or skier velocity during cutting than any other (p<0.0001 for both). The main variable that would change between subjects is their skiing ability and therefore this is what is causing the difference in the two performance parameters. Table 3 supports this result because it is expected that if a slalom skier has a lower success rate than he will have a lower average peak velocity. It is important to note that a higher average peak velocity does not always correspond to a higher average peak rope load. For example in Figure 6 subject 16 had a higher average peak rope load than subject 12. However, in Figure 8 subject 12 had a higher average peak skier velocity than subject 16. Furthermore, from Table 3 it can be seen that subject 12 also had a higher success rate than subject 16. This indicates that a quantitative assessment of skiing ability would include a combination of the desired high peak skier
velocity and low peak rope load. In other words, it is important to consider a skier or ski that allows for the skier to use rope load in the most efficient way.

Similarly to deep water starts a more detailed qualitative analysis of skier technique could be used to determine what allowed one subject to perform better than another. This could be very beneficial when attempting to improve a skier’s ability because it would be ideal if they could maintain a high level of performance while reducing the loads on the body. This would not only increase their performance but improve their endurance and general body fatigue during their ski sessions.

The average rope load results during deep water starts for all four skis were higher than those reported by Runciman (2011). He found that the tapered slalom skis he was testing had an average rope load of 1.97BW, compared to a range of 2.25 – 2.39BW for the four skis used in this study. However, the overall range of rope load during deep water starts in this study was found to be 1.74 – 2.74BW. Runciman (2011) also reported the average maximum velocities while cutting for an assortment of tapered skis, 127% of boat velocity. Runciman’s (2011) results are difficult to compare to the results of this study because he took a single, overall maximum while cutting for each skier and then averaged those value for all of his participants. The skier velocity results in this study were an average of the peak velocity achieved during each turn, and the range for the four skis was found to be 128 - 129% of boat velocity. Higher skier speeds would have been expected from the advanced skiers in our study. In addition to the difference in analysis procedure, it is challenging to compare the two studies because Runciman (2011) did not:
provide the same structure to their repeated activities, use a traditional slalom ski tow
boat with automatic speed control, use a slalom course, use the same length of ski rope or
use consistent ski sizes.

5 Conclusion

This study analyzed the impact of ski design and skier ability on dynamic performance
while slalom water skiing. The introduction of a more intensive experimental procedure
meant that our subject pool was limited to advanced skiers. The experimental procedure
was controlled to reduce the impact of weather, fatigue and inconsistent subject activities.

The typical peak rope load for an advanced skier during a deep water start is in the range
of 1.74-2.74 times body weight. It was not possible to suggest that one ski design resulted
in a statistically significantly lower peak rope load than another one. However, the skis
with the wider profile design did result in the lowest averages, which is what would be
expected. Therefore, data of this nature could be used as a tool to analyse the difference
in peak rope load during deep water starts that can be achieved on different ski designs.
In the future a study of this nature could be used to test ski design concepts and improve
product design capabilities in the water ski industry

The deep water start results do indicate that it could be possible to suggest that one
subject’s technique resulted in a lower peak rope load than another one. Rope load results
could be combined with a visual or quantitative assessment of skier technique in order to
improve the accuracy that a coach evaluates slalom performance during a deep water start.

The typical average peak rope load and skier velocity, for an advanced skier, during the cutting portion of a ski run is in the range of 1.41-2.74 times body weight and 113.71-135.43 % of boat speed. The results indicate that a wider profile ski will result in lower peak rope loads during cutting than one with a narrow profile. It was not possible to suggest that one ski design resulted in a significantly different average peak skier velocity than another one. Regardless, the analysis technique used in this study could be used in the future to evaluate the rope load and peak velocity achieved while skiing on different ski designs. A comparison between the performance of different designs could be used to determine that one ski is better than another.

Rope load and velocity results did indicate that it could be possible to suggest that one subject’s technique resulted in a different average resultant than another one while skiing in the slalom course. Therefore, this type of analysis combined with an evaluation of skier technique would provide a more detailed and accurate method for coaches to assess skier performance in a slalom course.

In the future the analysis used to evaluate performance during deep water starts and cutting in a slalom course, could improve product design capabilities and coaching techniques in the water ski industry. Data of this nature will provide an evaluation tool that was not previously available to manufacturers. This will improve their ability to analyse the performance being achieved on new ski designs and could be used to test ski
design concepts. Data of this nature could also provide a more accurate and detailed method for coaches to assess skier performance and thus improve their coaching capabilities.

6 Acknowledgements

For simplicity, all acknowledgements can be found after the main title page of this thesis.

7 References

For simplicity, a master reference list was used and can be found after Chapter 6.
Chapter 5: Biomechanical Analysis of Slalom Water Skiing: an in-depth look at a slalom cut
Biomechanical Analysis of Slalom Water Skiing: an in-depth look at a slalom cut

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Abstract

Water skiing has received little attention in research literature and has not utilized recent advancements in technology like other highly dynamic sports. In this study six advanced slalom skiers were recruited to test four different ski designs in the summer months of 2010. The goal being to detect performance differences achieved between ski designs and performance differences achieved by each skier. Uncontrollable factors were minimized using a well structured experimental procedure. An inertial measurement unit (IMU) was attached to the skis to provide ski roll, ski acceleration and deceleration. Statistical analysis suggested that there was a difference in the average peak roll achieved between the skis, but was unable to suggest a difference in the other performance parameters. The ranges for the average of each parameter were: 44.52°-59.41°, 5.16 m/s²-13.60 m/s² and -8.053 m/s² - -12.46 m/s². In contrast however, statistical analysis indicated that there was a difference in the performance achieved between the skiers, which is supported by the success rates in the slalom course. As expected, the subject with the highest success rate was amongst the top three highest for 10 of the 11 performance parameters and the subject with the lowest success rate was amongst the bottom two in all 11 parameters. The results show that this type of analysis could used to provide a more detailed performance assessment than what is currently available for product design and coaching. A more detailed assessment of performance will improve product design capabilities and coaching techniques.
1 Introduction

Water skiing requires a unique set equipment and access to a body of water, which gives it the reputation of being a luxury sport. Despite this, it has approximately 10 million annual North American participants and growing international participation, evident by its introduction to the Pan Am Games in 1995 [SGMA, 2003; “Pan American Games”, 2011].

Slalom skiing is one of the events featured in international competitions and when participated at a recreational level is considered to be an intermediate/advanced activity. The end objective for slalom skiing is to be able to ski in a slalom course, which consists of a series of buoys in the water that dictate the course of the skier. The skier must perform a sequence of oscillating left and right turns to travel on the outside of the buoys.

A common measure of performance is how many turns a skier is able to successfully complete on the outside of a buoy. The dimensions of the course are standardized however the activity can be made increasingly difficult by increasing boat speed and decreasing rope length, making it more difficult to reach around the buoy. A slalom turn involves a complex sequence of motions that occur in a relatively short amount of time. Ski acceleration, deceleration and orientation are a few of the important performance parameters that affect the ability for a skier to be successful in the slalom course. An analysis of these performance parameters could be used as a tool for assessing the overall performance of a skier. This would improve the detail used to evaluate skier performance and allow coaches to have more performance parameters other than successful turns around the buoys. A more detailed evaluation of skier performance would also improve
ski manufacturers ability to compare ski designs, which would lead to advancements in product design.

It is not only important to consider the performance parameters independently but also how they interact with each other. It is hypothesized that a higher resultant in one of the parameters is due to a higher resultant of another. For example, higher peak roll will lead to higher deceleration, which in turn leads to higher rope load and acceleration. To help identify which of the parameters are dependent on others, it is necessary to break down the different phases of a slalom cut and what reactions are taking place in each phase.

Maximizing personal performance is a goal that both recreational and competitive slalom skiers have and they often require coaching to achieve it. A results based coaching structure has been developed by Water Ski and Wakeboard Canada that uses a set of techniques to improve a skiers ability to complete successful turns in a slalom course (T. Van Winkle, personal communication, August 15, 2011). The coach is responsible for understanding the required technique so they can evaluate skier performance and assess if there is a problem and what is causing it [Water Ski and Wakeboard Canada, 2011]. Visual methods are most commonly used by coaches to evaluate performance and the effectiveness of this type of coaching philosophy depends on the accuracy of their evaluation. Quantitative data collected from a skier in a slalom course could be used as an additional tool for coaches to assess performance and improve the accuracy of their evaluation. Therefore, it would improve the coaching capabilities in the water ski industry.
An inertial measurement unit (IMU) is the type of transducer that could be implemented to provide this type of quantitative data. The basic theory and applications of accelerometers and gyroscopes date back several years in literature. Advancements in technology have allowed both types of transducers to decrease in size while being more accurate and robust. This has significantly increased the types of applications that IMUs can be used for. Furthermore, the development of IMUs, which combine accelerometers, gyroscopes and magnetometers, has improved the quantitative analysis of highly dynamic sports. Water skiing is an example of a highly dynamic sport that has not received the same type of attention in research literature. This is most likely due to the many challenges that present themselves with respect to the natural environment of water skiing.

One author was able to collect skier velocity and rope load during different water skiing activities for a group of intermediate skiers [Runciman, 2011]. Another, published a description and applications of instrumentation that could be used to collect a variety of performance parameters. However, they were unable to support their work with any experimental data [Macken, 1997].

The purpose of this study was to fill the void in literature and provide quantitative data for advanced slalom skiers, while implementing a controlled environment to improve the quality of data, from Runciman (2011). This article will provide details of the methodology that was used to collect and analyse the experimental data. Details will be
given about how the effects of the uncontrollable factors were minimized to produce a higher quality data set. It will be discussed how the results from the study could be used as a tool for improvements in assessing skier performance and how the improved assessment will lead to better coaching capabilities and product design.

2 Methods

Data was collected throughout three days in the summer months of 2010, at Lighthouse Lake Water Sports Centre, near Bancroft, Ontario. Six human participants were recruited to be the test subjects, after the study received ethics approval from the University of Guelph Ethics Committee. The subjects were recruited based on their skiing ability, where the requirements were that they be able to ski two passes of a slalom course four times throughout a test day. This made the skill level of our subject pool to be advanced slalom skiers. A summary of the human participants can be seen in Table 1.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Weight (lbs)</th>
<th>Height (cm)</th>
<th>Forward Foot</th>
<th>Years Slalom Skiing at Current Skill Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>41</td>
<td>79.38</td>
<td>177.80</td>
<td>L</td>
<td>More than 20</td>
</tr>
<tr>
<td>12</td>
<td>51</td>
<td>86.18</td>
<td>177.80</td>
<td>R</td>
<td>11-15</td>
</tr>
<tr>
<td>13</td>
<td>28</td>
<td>90.72</td>
<td>190.50</td>
<td>R</td>
<td>11-15</td>
</tr>
<tr>
<td>14</td>
<td>30</td>
<td>81.65</td>
<td>177.80</td>
<td>L</td>
<td>Less than 5</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>75.30</td>
<td>187.96</td>
<td>L</td>
<td>11-15</td>
</tr>
<tr>
<td>16</td>
<td>38</td>
<td>74.39</td>
<td>175.26</td>
<td>R</td>
<td>16-20</td>
</tr>
</tbody>
</table>

One experimental test run consisted of initializing the data collection program with the ski and skier on the dock. Then the skier was taken to one end of the slalom course where they performed a deep water start, followed by two passes of the course. A pass of the
course consists of a set-up cut, entrance cut where the skier enters the course through the entrance gates, followed by an oscillating sequence of six left and right turns (three of each) before exiting the course through the exit gates. A diagram of the course can be seen in Figure 1.

![Diagram of slalom course including entrance gates (x), skier path and buoys 1–6 (o) and sample dimensions [“International Waterski & Wakeboard”, 2010].](image)

The IMU chosen was (3DM-GX2, Microstrain, Inc., Williston, Vermont) mounted to the water ski directly in front of the front binding. A custom fabricated plate was fastened to the ski, using the same bolt footprint as the front binding, and extended out towards the
tip. The IMU housing was wrapped in plastic and strapped to the plate. Data from the sensor was transmitted, via custom RF transmission system, to a computer (Acer Aspire One ZG5, Acer America Corporation, Mississauga, ON) located in the toe boat. The RF transmission system consisted of two custom designed RF units, one located on the ski and the other was connected to the computer via universal serial bus (USB) port. Each unit had two RF transceiver modules (nRF2401, Nordic Semiconductor ASA, Tiller, Norway) that were operated by a micro controller. The data was parsed by the computer using a custom data collection program (Labview 8.2, National Instruments Corporation, Austin TX). The data output from the sensor was received as a digital signal and then was converted to an analogue output via the data collection program.

Each subject was required to perform one test run on each of the four skis. The skis varied in classification from “performance” to “tournament”. A brief summary of the skis can be found in Table 2 and a sample ski profile can be seen in Figure 2. A randomized procedure was used to help minimize the effects of fatigue and changing weather throughout the day. To further minimize the factors that would influence the results, all of the ski runs were done on the same slalom course with the same rope length, 17.9 m. Boat speed was controlled using an automatic control system that was set to 51.5 km/h for all of the experimental test runs.
Table 2: Summary of the four ski models used

<table>
<thead>
<tr>
<th></th>
<th>Ski A</th>
<th>Ski B</th>
<th>Ski C</th>
<th>Ski D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (cm)</td>
<td>170</td>
<td>170</td>
<td>170</td>
<td>170</td>
</tr>
<tr>
<td>Width at Widest Point (cm)</td>
<td>17.28</td>
<td>18.53</td>
<td>20.34</td>
<td>17.26</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>2.81</td>
<td>2.81</td>
<td>2.75</td>
<td>2.00</td>
</tr>
<tr>
<td>Classification</td>
<td>Tournament</td>
<td>Tournament</td>
<td>Performance</td>
<td>Tournament</td>
</tr>
</tbody>
</table>

Figure 2: Sample ski profile.

Wind was monitored using a temporary weather station. Data was collected by a data logger (SynphoniePLUS, NRG Systems Inc, Hinesburg, Vermont) from an anemometer (#40C, NRG Systems Inc, Hinesburg, Vermont), located such that it was exposed to similar wind conditions as the slalom course.

Data files were processed using Microsoft Excel (Microsoft Canada Co, Mississauga, Canada) after each of the test days. The orientation matrix was used to find pitch, roll and heading, which were then used to identify the left and right turns within each file. It was defined that the quantitative threshold for the start and end of a turn was when roll crossed over 0°. For a left turn the roll values were positive and for a right turn the values were negative. During one turn each of the performance parameters will have their respective peaks, however they do not all occur at the same time. A slalom turn can be broken down into five distinct phases: approach, apex, exit, wake crossing and next turn initiation. Deceleration was calculated during the approach and apex phases, while acceleration was calculated during the exit phase. For the three performance parameters
(roll, acceleration and deceleration) both turn peak and the integration of the parameter profile were calculated. All of the integrations are the area under the curve with respect to time. The acceleration data was filtered using a moving average, where five data points were used as the averaging window.

The performance parameters were analyzed using a generalized linear mixed-model for statistical significance. When testing the performance of the skis, factors included in the model were ski turn and skier as well as their interactions. A comprehensive residual analysis was used to assess the assumptions of the ANOVA. Overall normality was assessed by a Shaprow-Wilk test, a Kolmogorov-Smirnov test, a Cramer-von Mises test, and an Anderson-Darling test. In order to look for patterns in the data that suggest outliers, unequal variance or other problems, residuals were plotted against predicted values and explanatory variables. If there was a need for data transformation or data was presented as a percent, analyses were done on a logit or log scale. Finally, if the overall f test was significant a tukey test was applied to determine the adjusted p-value. (SAS Institute Inc. 2004. SAS OnlineDOC (R) 9.1.3. Cary, NC: SAS Institute Inc)

3 Results

The average wind speed recorded by the anemometer for the three days were 2.37, 3.03 and 0.87 m/s. Wind direction was approximated to be consistently 5-10° off the center line of the slalom course. Wave height was not recorded but it was not determined to have a significant impact on the results. The impact of the weather on the final results
was minimal since whenever possible each subject completed one pass with the wind and another into the wind.

Due to the high demand of each data collection day the initial test requirements were altered. The challenge of being expected to ski two passes of a slalom course on new equipment was underestimated and the recruited participants were not required to do so. Each subject was still required to ski the length of the course and complete as many “good” slalom cuts as possible and the number of completed turns around a buoy was taken as a performance parameter. The number of good turns and successful turns completed around a buoy can be seen in Table 3. It was anticipated that all skiers would have a success rate of 100%.

<table>
<thead>
<tr>
<th>Subject 11</th>
<th>Subject 12</th>
<th>Subject 13</th>
<th>Subject 14</th>
<th>Subject 15</th>
<th>Subject 16</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Turns</td>
<td>106</td>
<td>90</td>
<td>75</td>
<td>45</td>
<td>64</td>
</tr>
<tr>
<td># of Successful Turns</td>
<td>94</td>
<td>73</td>
<td>17</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>Success Rate (%)</td>
<td>88.7</td>
<td>81.1</td>
<td>22.7</td>
<td>57.8</td>
<td>0</td>
</tr>
</tbody>
</table>

For simplicity the results in Figure 3 and Figure 4 are all from a left turn, which occurs when the skier is on the right side of the boat. Figure 3 shows the typical data collected during a left turn and in this case it is from Subject 11. In the approach phase, the ski has transitioned from negative roll values from the previous right turn, starts at 0° and increases, deceleration occurs and skier velocity decrease thus causing the rope load to
decrease. This portion of the turn is when the skier adjusts their deceleration to have the right timing for completing their turn around the buoy (Figure 3 from 0-30%).

As the skier enters the turn apex, the skier begins to change their direction of travel, roll reaches its peak value, while rope load and velocity reach their minimum values. During this portion of the turn the skier physically travels around the buoy and by the end of this phase the ski is pointed back across the wake and has fully changed direction (Figure 3 from 30-60%).

As the skier exits the turn, roll decreases but at a slower rate than in the approach phase, rope load begins to increase again and the skier generates acceleration. Velocity increases as acceleration continues and rope load reaches its peak value before beginning to decrease (Figure 3 from 60-85%).

When the skier crosses the wake roll and rope load continue to decrease as the skier reaches peak velocity. There are two identifiable bumps in the load and roll profiles as the skier absorbs the wakes (Figure 3 from 85-95%).

As the skier initiates their next turn velocity begins to decrease as rope load and roll continue to decrease until roll reaches 0º again. During this portion of the turn the skier has already crossed the wake however they are often required to absorb continued oscillations from the impact after the second wake (Figure 3 from 95-100%).
Figure 3: Typical left turn ski roll, ski acceleration, skier velocity and rope load for subject 11, who had an overall success rate of 88.7%. The five phases of a slalom cut can be identified: approach, apex, exit, wake crossing (WC) and next turn initiation (NTI).

The results shown in Figure 3 are a generalization of what was found in large majority of the turns from all the skiers. However, the timing of each phase and the resultant performance parameters can change slightly from one turn to the next. The most obvious of this was occurring from Subject 15. Similar sample profiles from one of their left turns can be found in Figure 4. The same phases can be identified however the peak parameters are smaller in magnitude and occurring at different times. This supports other results that indicate Subject 15 is skiing at a lower level than the rest of the subject pool.
Figure 4: Typical left turn ski roll, ski acceleration, skier velocity and rope load for subject 15, who had an overall success rate of 0%. The five phases of a slalom cut can be identified: approach, apex, exit, wake crossing (WC) and next turn initiation (NTI).

Not exclusively peak roll, acceleration and deceleration are the important parameters from the IMU but it is also important to consider the integral of each profile during each turn. The integrals will give a more detailed “picture” of the cumulative result during a turn and are all summation of the parameter verses time. Figure 5 and Figure 6 show each skier’s overall average integral of roll and peak roll for dominant and non-dominant turns. Statistical analysis suggests that at least one of the subjects had a significantly different result than another subject (p<0.0001 for both integral and peak resultant). The skier with the highest integral average on all of the skis was Subject 16 for dominant turns and Subject 11 for non-dominant turns, 109.40 and 104.68 °·s. The skier with the lowest integral average on all of the skis was Subject 15 for both dominant and non-dominant turns, 68.79 and 67.33 °·s. The skier with the highest peak average on all of the skis was Subject 12 for dominant turns and Subject 11 for non-dominant turns, 59.41 and 56.80 °. The skier with the lowest peak average on all of the skis was Subject 15 for dominant turns and Subject 13 for non-dominant turns, 47.03 and 44.52 °. Error bars for
the integral results represent upper and lower 95% confidence intervals and error bars for the peak results represent the calculated pooled standard error. Both have been calculated from the statistical analysis.

Figure 5: Subject overall average integral of roll and peak roll for dominant turns. The highest averages were 109.40°·s and 59.41°, and lowest averages were 68.79 °·s and 47.03 °. There was a significant difference between the skiers for both performance parameters (p<0.0001). Error bars for the integral represent upper and lower confidence intervals and error bars for the peak represent pooled standard error.
Figure 6: Subject overall average integral of roll and peak roll for non-dominant turns. The highest averages were 104.68°·s and 56.80°, and lowest averages were 67.33 °·s and 44.52 °. There was a significant difference between the skiers for both performance parameters (p<0.0001). Error bars for the integral represent upper and lower confidence intervals and error bars for the peak represent pooled standard error.

Figure 7 and Figure 8 show the overall average integral of roll and peak roll for each ski for dominant and non-dominant turns. Statistical analysis suggests that there was no significant difference in the integral of roll produced from the different skis (p=0.3464). However, it does suggest that there is a significant difference in the peak roll produced from the different skis (p=0.0014). Although not statistically significant, the ski with the highest integral average was Ski D for dominant turns and Ski A for non-dominant turns, 96.44 and 88.47 °·s respectively. The ski with the lowest integral average was Ski A for dominant turns and Ski C for non-dominant turns, 87.83 and 83.42 °·s respectively. The ski with the highest peak average was Ski A for both dominant and non-dominant turns, 54.18 and 52.51 °. The ski with lowest peak average was Ski B for both dominant and non-dominant turns, 52.96 and 48.92 °. Ski B had a statistically lower average peak roll than Ski A and Ski D (p=0.002 and p=0.0178). Error bars for the integral results represent upper and lower 95% confidence intervals and error bars for the peak results.
represent the calculated pooled standard error. Both have been calculated from the statistical analysis.

![Figure 7: Ski overall average integral of roll and peak roll for dominant turns. The highest averages were 96.44°·s and 54.18°, and lowest averages were 87.83 °·s and 52.96 °. There was a significant difference between the skis for peak roll but not for integral of roll (p=0.0014 and p=0.3464). Error bars for the integral represent upper and lower confidence intervals and error bars for the peak represent pooled standard error.](image-url)
Figure 8: Ski overall average integral of roll and peak roll for non-dominant turns. The highest averages were 88.47°·s and 52.51°, and lowest averages were 83.42°·s and 48.92°. There was a significant difference between the skis for peak roll but not for integral of roll (p=0.0014 and p=0.3464). Error bars for the integral represent upper and lower confidence intervals and error bars for the peak represent pooled standard error.

Figure 9 shows the overall average integral of deceleration of each skier for dominant and non-dominant turns. Statistical analysis suggests that at least one of the subjects had a significantly different result than another subject (p<0.0001). The skier with the highest average on all of the skis was Subject 11 for both dominant and non-dominant turns, -9.19 and -9.26 m/s²·s. The skier with the lowest average on all of the skis was Subject 15 for both dominant and non-dominant turns, -4.34 and -4.35 m/s²·s. The error bars shown in the figure represent the calculated pooled standard error from the statistical analysis.
Figure 9: Subject overall average integral of deceleration for dominant and non-dominant turns. The highest and lowest dominant turn results were -9.19 and -4.34 m/s$^2 \cdot s$. The highest and lowest non-dominant turn results were -9.26 and -4.35 m/s$^2 \cdot s$. There was a significant difference between the skiers ($p<0.0001$). Error bars represent pooled standard error.

Figure 10 shows each ski’s overall average integral of deceleration for dominant and non-dominant turns. Statistical analysis suggests that there was no significant difference between the skis ($p=0.1341$). Although not statistically significant, the ski with the highest average was Ski D for dominant turns and Ski A for non-dominant turns, -7.48 and -7.96 m/s$^2 \cdot s$ respectively. The ski with the lowest average was Ski B for both dominant and non-dominant turns, -6.77 and -7.61 m/s$^2 \cdot s$. The error bars shown in the figure represent the calculated pooled standard error from the statistical analysis.
Figure 10: Ski overall average integral of deceleration for dominant and non-dominant turns. The highest and lowest dominant turn results were -7.48 and -6.77 m/s²·s. The highest and lowest non-dominant turn results were -7.96 and -7.61 m/s²·s. There was no significant difference between the skis (p=0.1341). Error bars represent pooled standard error.
Figure 11 shows the overall average peak deceleration for each skier for all turns. The dominant and non-dominant turns were combined because statistical analysis showed that there was no difference between the two. However, the statistical analysis did suggest that at least one of the subjects had a statistically significant, different result than another (p<0.0001). The skier with the highest average on all of the skis was Subject 16, -12.46 m/s\(^2\). The skier with the lowest average on all of the skis was Subject 13, -8.053 m/s\(^2\). The error bars shown in the figure represent the calculated pooled standard error from the statistical analysis.
Figure 12 shows each ski’s overall average peak deceleration. The dominant and non-dominant turns were again combined because statistical analysis showed that there was no difference between the two. Statistical analysis also suggest that there was no statistical difference in the peak deceleration produced from the different skis (p=0.1134). Although not statistically significant, the ski with the highest average was Ski D, 11.22 m/s$^2$. The ski with the lowest average was Ski B, -10.39 m/s$^2$. The error bars shown in the figure represent the calculated pooled standard error from the statistical analysis.

Figure 12: Ski overall average peak deceleration for all turns. The highest average was -11.22m/s$^2$ and lowest average was -10.39m/s$^2$. There was no significant difference between the skis (p=0.1134). Error bars represent the pooled standard error.
Figure 13 and Figure 14 show each skier’s overall average integral of acceleration and peak acceleration for dominant and non-dominant turns. Statistical analysis led to the conclusion that one of the subjects had a statistically significant, different result in both parameters than another (p<0.0001 for both integral and peak resultant). The skier with the highest integral average on all of the skis was Subject 16 for dominant turns and Subject 11 for non-dominant turns, 6.18 and 5.50 m/s²·s respectively. The skier with the lowest integral average on all of the skis was Subject 15 for both dominant and non-dominant turns, 2.08 and 2.07 m/s²·s. The skier with the highest peak average on all of the skis was Subject 11 for dominant turns and Subject 16 for non-dominant turns, 13.60 and 11.62 m/s² respectively. The skier with the lowest peak average on all of the skis was Subject 15 for both dominant and non-dominant turns, 6.06 and 5.16 m/s². Error bars shown in the two figures represent upper and lower 95% confidence interval, calculated from the statistical analysis.
Figure 13: Skier overall average integral of acceleration and peak acceleration for dominant turns. The highest averages were 6.18m/s²·s and 13.60m/s², and lowest averages were 2.08m/s²·s and 6.06m/s². There was a significant difference between the skiers for both parameters (p<0.0001). Error bars represent upper and lower confidence intervals.

Figure 14: Skier overall average integral of acceleration and peak acceleration for non-dominant turns. The highest averages were 5.50m/s²·s and 11.62m/s², and lowest averages were 2.07m/s²·s and 5.16m/s². There was a significant difference between the skiers for both parameters (p<0.0001). Error bars represent upper and lower confidence intervals.
Figure 15 and Figure 16 show the overall average integral of acceleration and peak acceleration of each ski for dominant and non-dominant turns. Statistical analysis led to the conclusion there was no statistical difference in both parameters produced from the different skis (p=0.9314 and p=0.9326 for integral and peak respectively). Although not statistically significant, the ski with the highest integral average was Ski C for dominant turns and Ski A for non-dominant turns, 4.92 and 4.54 m/s²·s respectively. The ski with the lowest integral average was Ski A for dominant turns and Ski C non-dominant turns, 4.75 and 4.18 m/s²·s respectively. The ski with the highest peak average was Ski D for dominant turns and Ski B for non-dominant turns, 11.18 and 9.95 m/s² respectively. The ski with lowest peak average was Ski C for both dominant and non-dominant turns, 10.67 and 9.13 m/s². Error bars for the integral results represent pooled standard error, calculated from the statistical analysis.

Figure 15: Ski overall average integral of acceleration and peak acceleration for dominant turns. The highest averages were 4.92 m/s²·s and 11.18 m/s², and lowest averages were 4.75 m/s²·s and 10.67 m/s². There was no significant difference between the skis for both parameters (p=0.9314 and p=0.9326). Error bars represent pooled standard error.
Figure 16: Ski overall average integral of acceleration and peak acceleration for non-dominant turns. The highest averages were 4.54m/s$^2\cdot$s and 9.95m/s$^2$, and lowest averages were 4.18m/s$^2\cdot$s and 9.13m/s$^2$. There was no significant difference between the skis for both parameters ($p=0.9314$ and $p=0.9326$). Error bars represent pooled standard error.

4 Discussion

The recorded wind speed and direction were relatively similar for all three of the test days. One important consideration is that the subjects did not all ski on the same test days and in some cases subjects completed test runs on more than one day. Due to this, if one day affected performance significantly more than another, it might affect the ability to compare between the skiers. An investigation into the subjects that skied over multiple test days concluded that there was no noticeable impact of the different skiing conditions, on their success rate results. Therefore, there will be a negligible impact on the results of this study. Skis were all used equally over the three test days so the effect on the analysis between the skis will also be negligible. A detailed analysis of the variability within a skier was not conducted.
Typical data profiles shown in Figure 3 demonstrate how it is possible to identify the
different phases of a slalom cut and the interaction between performance parameters. The
timing of when a specific peak parameter occurs in one of the phases has a cascading
effect on the result in the preceding phases and overall result of the turn. One key
example of this is in the exit phase, when the skier is generating acceleration. They must
have first reached a high peak roll in the turn apex in order to build enough rope load,
which they can use to generate high accelerations. Furthermore, they need to ensure that
they have created enough acceleration before the wake crossing phase to reach a high
peak velocity because it is difficult to generate more once they have started to cross the
wake. In fact, it is a challenge not to loose momentum during the complex kinematics
occurring during the wake crossing phase and this is often one of the hardest things for an
amateur skier to accomplish. If a skier has not accomplished all of this and reached a high
peak velocity is less likely that they will be able to successfully complete their next turn
around the next buoy.

The scenario previously described can be seen in Figure 4, which shows the same
parameter profiles as the previous figure only this time for Subject 15. As seen by the
success rate results in Table 3, Subject 15 was not able to complete any of their turns
around the buoys. In Figure 4 it can be seen that Subject 15 was reaching their peak roll
at approximately the same time during the apex, however it is lower in magnitude. As
expected this correlates with the skier not being able to produce the same deceleration or
create a high rope load. With a lower peak rope load that also is occurring earlier in the
turn, the skier is unable to generate the same type of acceleration or peak velocity. The
peak velocity is also occurring at the very end of the turn, which indicates that after they cross the wake they are still trying to accelerate the ski to allow them to get out far enough to the side of the boat. This in turn would affect the timing of their next turn initiation.

Even though all the subjects were advanced slalom skiers the analysis procedure developed in this study was successful in detecting differences in performance between the skiers. Furthermore, the results were in agreement with what was expected based on the success rate of each skier in the course. The skier with highest success rate did not always achieve the highest resultant performance parameter however they were always in the top grouping with respect to performance. For example, Subject 11 achieved the highest success rate but only had the highest resultant in 6 of the 11 performance parameters. They were however amongst the top three highest in 10 of the 11 parameters. Similarly, the two subjects with the lowest success rates were always in the lower grouping with respect to performance. Subject 15 achieved the lowest success rate and had the lowest resultant in 10 of the 11 performance parameters and was in the bottom two lowest in all 11 parameters. These results indicate that our analysis procedure appropriately assessed skier performance. It therefore could be used as tool for improved analysis of skier performance that could be implemented to increase coaching capabilities and product design.

For all the results shown in Figure 5 - Figure 16 it was not seen that the highest peak always led to the highest integral. This is expected since the profile shape plays a large
roll in the calculated integral. For example, if a skier is able to hold a slightly smaller peak roll for longer they will produce a larger integral of roll. However, it would be expected that those skiers capable of producing high peaks will result in high integrals. This is supported by the result because there were three skiers (Subject 11, Subject 12 and Subject 16) who had the higher peak averages and also had the higher integrals of each parameter. In the same regard, Subject 15 had the lowest integral of every parameter and also produced the lowest peaks in every parameter except for deceleration. These findings are supported by the success rate results found in Table 3, where Subject 11, Subject 12 and Subject 16 had the highest success rate and Subject 15 had the lowest.

The ski results did not show the same type of trend and in some cases the highest peak average for a parameter led to the lowest integral average of that parameter. This is not what would be expected but can be explained by the fact that there is no statistically significant difference between the skis for all the parameters except peak roll. Thus, the results are similar enough that it is harder to make conclusions based on the trend found amongst the skis. It should be noted that peak roll is the only parameter where a ski was highest for both dominant and non-dominant turns and another ski was lowest for both dominant and non-dominant. This is what was expected because skis are symmetrical and therefore one ski would not have an advantage based on what edge is being used.

Another point of interest for all the results shown in Figure 5 - Figure 16 is that there was no common trend within each parameter of highest-to-lowest between dominant and non-dominant turns. This would be expected when analyzing the skis due to the fact that there
was not a significant difference between them for all the parameters except peak roll. However, in the case of the skiers it would have been expected to see more situations where a skier was able to achieve the highest result for both dominant and non-dominant turns. Without a more detailed investigation it is hard to determine why this was the situation but it might be due to one skier being more proficient with both types of turns than another. For example a skier who achieved the highest result during dominant turns, might not have during non-dominant turns because their performance drops off, on the non-dominant side, more than another skier.

As previously discussed it is expected that the parameters are dependent on each other and a skier who is capable of achieving high peak and integration of roll will be able to produce more deceleration and acceleration. This was seen in the results in the non-dominant case with Subject 11, where they had the highest peak and integration of roll as well as integration of acceleration and deceleration. These performance results are expected because Subject 11 had the highest success rate in the slalom course. It is interesting to note that even though the subject was able to achieve the highest integration of acceleration and deceleration they did not have the highest peaks in either parameter.

The dependence between parameters was also seen in the average results from each of the skis. For example in the non-dominant case Ski A had the highest peak and integration of roll as well as integration of acceleration and deceleration. Although, the trend might be considered more of a coincidence in this case since it was proven that there was not a statistically significant difference between the skis, except for peak roll.
The only parameter that had no significant difference between dominant and non-dominant turns was peak deceleration. This is not what was expected because peak deceleration occurs during the turn apex phase which is also when peak roll occurs and is typically when there would be a difference between dominant and non-dominant turns.

It is unclear why peak roll is the only parameter that was found to have a significant difference between the skis. It is hypothesized that under the test conditions the subjects were able to generate similar accelerations from all the ski designs. If the difficulty of the slalom course was increased, by increasing boat speed and decreasing rope length, it is expected that differences in performance would be more identifiable. These changes would make it subsequently more difficult for the subjects to adjust to using new equipment and it might be required to allow the subjects to practice before test days. Furthermore, it was not expected that Ski A would result in the highest average peak roll because it was not the most aggressive ski design. The results that Ski B had a statistically significant lower average than Ski A and Ski D also do not correspond to the qualitative survey, in which Ski A ranked worst in the performance questions. For the survey, each ski was ranked by the subjects and a total number of points for each question was calculated. Ski D had the highest point total for performance question with 153 points, Ski B was second highest with 150 points and Ski A was lowest with 116 points (Appendix C).
The lack of statistical significance when comparing the performance between skis was not anticipated. However, the power of the statistical analysis could be increased by increasing the number of human participants. It was not feasible to have collected more data over one summer but it is expected that once more human participants are used the data will become stronger. In addition, it should be taken into consideration that only two ski designs be compared in further tests. This will allow for more repetitions of each activity throughout the test day and will be easier to detect when one is out performing the other.

5 Conclusion

A versatile quantitative data set was produced from the designed instrumentation system and methodology. The uncontrollable factors that present themselves in the natural environment of slalom water skiing were effectively minimized.

The data streams produced from the IMU on the water ski were used to provide ski roll profiles which could identify left and right turns. A break down of each turn and the acceleration and deceleration data streams were used to identify five phases within a slalom cut and what key performance benchmarks occur during them.

During each turn the peak roll, integral of roll, peak acceleration and deceleration, and integral of acceleration and deceleration were calculated. The ranges for the average of each parameter were: 44.52°-59.41°, 67.33°·s-109.401°·s, 5.16 m/s²-13.60 m/s², -8.053 m/s² - -12.46 m/s², 2.07 m/s²·s – 6.18 m/s²·s and -4.34 m/s²·s - -9.26 m/s²·s. A statistical
analysis was only able to identify a difference between the ski designs for one of the performance parameters, peak roll.

Statistical analysis was able to identify the expected difference between skiers for all of the performance parameters. In addition, based on the success rate results each subject achieved their expected level of performance. The subject with the highest success rate was amongst the top three highest for 10 of the 11 performance parameters and the subject with the lowest success rate was amongst the bottom two in all 11 parameters.

The hypothesis that the performance parameters are dependent on each other was supported by the quantitative results. In the skiers included in this study, those that were able to produce higher peak roll and integration of roll were able to produce more ski acceleration and deceleration. These same skiers also had a higher success rate in the slalom course.

6 Acknowledgements

For simplicity, all acknowledgements can be found after the main title page of this thesis.

7 References

For simplicity, a master reference list was used and can be found after Chapter 6.
Chapter 6 – Conclusion and Future Considerations
6.1 Conclusion and Future Considerations

The purpose of this study was to fill the void in research literature and provide quantitative data for advanced slalom skiers. The data and analysis procedure would act as the first step in providing improved methods for assessing skier performance. An improved assessment method could be used as an additional tool for water ski coaches to evaluate skier performance. It could also be used as a tool for ski manufacturers to evaluate performance on different ski designs. Therefore, the data and analysis procedure could be used to improve product design and coaching capabilities in the water ski industry.

The instrumentation system and methodology were successfully implemented in order to collect quantitative data from six advanced slalom skiers. The performance parameters of interest were skier velocity, ski roll, ski acceleration and deceleration and rope load. The use of a well structured experimental procedure was successful in minimizing the uncontrollable factors that present themselves in the natural environment of water skiing.

The instrumentation system was found to be acceptable for the harsh environment and mounting systems were successful. The only issue encountered throughout the test was intermittent signal loss with the IMU RF transceiver system. The effect was minimized by adjusting the receiver located in the tow boat. Further troubleshooting would be required to fully rectify the issue.
The data, in combination with a statistical analysis, revealed a significant difference between the performance of the skis for only two of the parameters, rope load and peak roll. It was expected that there would be a significant difference for all of the performance parameters and the unexpected result could be due to: skier skill compensating for design differences or low statistical power within the data set. It is possible that the skill level of the skiers was high enough that they were able to achieve high performance from a wide range of ski designs. In the future it would be interesting to demand higher performance from the skiers and see if the results remained consistent. With respect to skier velocity, it is suggested that a higher update rate GPS unit be used. It is possible that the 5Hz unit was not picking up the actual peaks during each turn. In the future only comparing two of the skis and increasing the number of human participants would increase the statistical power of our data.

The data was able to detect when skiers were achieving different performance results than another skier. Therefore, the analysis techniques developed in this study could be used to assess skier performance in more detail than methods that are currently practiced. An improved method for analyzing skier performance could be used as an additional tool for coaches to evaluate skiers. This would increase their effectiveness when trying to determine if a problem exists and what the cause of the problem is. Similarly, an improved method for analyzing skier performance could be used by ski manufacturers to evaluate performance on different ski designs. This would increase their ability assess what characteristics of the ski design are effecting performance and therefore lead to advancements in product design.
References


Appendices
Appendix A: Sample calibration procedure for the load transducer

A calibration curve for the load transducer was created for each of the three experimental test days. To generate a Force vs Voltage diagram, data was collected while a series of weights (0kg, 5kg, 10kg and 15kg) were hung from the transducer. Equation 1 was used to determine the force produced from each of the weights.

\[ \text{Force} = \text{mass} \times 9.81 \quad \text{Equation 1} \]

A sample calculation for the 5kg mass can be seen below.

\[ \text{Force} = \text{mass} \times 9.81 \]
\[ \text{Force} = 5\text{kg} \times 9.81\text{m/s}^2 \]
\[ \text{Force} = 49.05\text{N} \]

The average voltage while the 5kg mass was hung from the transducer, was calculated and used to plot point A on the calibration curve seen in Figure 1. This was repeated for a mass of 0kg, 10kg and 15kg and then a linear model was fit to the data.
Figure 1: Calibration curve generated for day 1. The linear model equation was used to determine rope load given the voltage output during each experimental test run.

The equation of the linear model could then be used to calculate rope load given the voltages readings from the experimental test runs. A sample calculation can be seen below.

\[
\text{RopeLoad} = (208.33 \times \text{Voltage}) + 0.0833
\]

\[
\text{RopeLoad} = (208.33 \times 0.069) + 0.0833
\]

\[
\text{RopeLoad} = 14.46N
\]
Appendix B: Sample qualitative survey

Biomechancial Performance Factors of Slalom Waterskiing
- Research Survey -

Investigators: Jordan Bray-Miners  Advisor: John Runciman

Instructions to study participants: Please complete Section 1 of this survey before taking part in any of the test runs. Please complete Section 2 of this survey after you have completed all the test runs. Should you choose, you may opt to not complete any part of this survey.

Section 1- Background

General Physical Condition.
Please rank the following by circling the most appropriate response.

Name:
Address:

1. Weight:
2. Height(approximately):
3. I could comfortably,
   
   ○ Run 5 miles
   ○ Jog a mile
   ○ Run 2 flights of stairs
   ○ Walk a mile
   ○ None of these

4. Do you exercise regularly, not including water skiing?
   ○ Yes
   ○ No

5. If yes, on average how many times per week?
   ○ 1-2
   ○ 3-4
   ○ 5-6
   ○ 7 or more
Skiing Background Information

6. How many years have you been water skiing?
   - 0  0  0  0  0
   - Less than 5  5-10  10-15  15-20  20 or more

7. How many years have you been slalom skiing?
   - 0  0  0  0  0
   - Less than 5  5-10  11-15  16-20  More than 20

8. Have you ever been professionally coached?
   - 0  0
   - Yes  No

9. If yes, when was your last lesson?
   - 0  0  0  0  0
   - This ski season  1-3 years ago  4-6 years ago  7-10 years ago  More than 10 years ago

10. What is your current skill level?
    - 0  0  0  0  0
    - Competitive  Advanced non-competitive  Intermediate  Struggling intermediate

11. How many years have you been at this skill level?
    - 0  0  0  0  0
    - Less than 5  5-10  11-15  16-20  More than 20

12. Have you ever been at a higher skill level?
    - 0  0
    - Yes  No

13. If yes, how would you classify that skill level?
    - 0  0  0  0  0
    - Competitive  Advanced non-competitive  Intermediate  Struggling intermediate

14. On average how many months of the year do you water ski?
15. On average how many days do you water ski during those months?

<table>
<thead>
<tr>
<th></th>
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<th>2</th>
<th>3</th>
<th>4</th>
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16. What would be the daily typical number of runs for those days?

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<th>5-6</th>
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<td>5-6</td>
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<td>More than 6</td>
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17. What would be the daily typical minutes per run?

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<th>2-5</th>
<th>5-10</th>
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<td>2-5</td>
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<tr>
<td>5-10</td>
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<tr>
<td>More than 10</td>
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18. Have you ever obtained an injury while water skiing?

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
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<tbody>
<tr>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td></td>
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</tr>
</tbody>
</table>

19. If yes, has it affected your ability to ski at your maximum skill level and please explain your injury?

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
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<tbody>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
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## Section 2 – Follow up survey

*Please rank the following characteristics by giving each ski combination used a “grade”.*

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<th>Ski 1</th>
<th>Scale</th>
<th>Ski 2</th>
<th>Scale</th>
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<tbody>
<tr>
<td>Poor</td>
<td>Good</td>
<td>Excellent</td>
<td>Poor</td>
</tr>
<tr>
<td>Acceleration</td>
<td>1 2 3 4 5</td>
<td>Acceleration</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Deceleration</td>
<td>1 2 3 4 5</td>
<td>Deceleration</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Responsive</td>
<td>1 2 3 4 5</td>
<td>Responsive</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Smooth</td>
<td>1 2 3 4 5</td>
<td>Smooth</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Rope load pulling on your arms during slalom run</td>
<td>1 2 3 4 5</td>
<td>Rope load pulling on your arms during slalom run</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Rope load pulling on your arms during deep water start</td>
<td>1 2 3 4 5</td>
<td>Rope load pulling on your arms during deep water start</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Ability to initiate turns</td>
<td>1 2 3 4 5</td>
<td>Ability to initiate turns</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Ability to “cut” through the wake</td>
<td>1 2 3 4 5</td>
<td>Ability to “cut” through the wake</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Overall effort needed to complete run</td>
<td>1 2 3 4 5</td>
<td>Overall effort needed to complete run</td>
<td>1 2 3 4 5</td>
</tr>
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</table>

**Comments:**

**Comments:**
<table>
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<th>Scale</th>
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<th>Acceleration</th>
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<tr>
<td>Rope load pulling on your arms during slalom run</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Rope load pulling on your arms during deep water start</td>
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<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>Ability to initiate turns</td>
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<td>3</td>
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<td>Ability to “cut” through the wake</td>
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<td>5</td>
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<tr>
<td>Overall effort needed to complete run</td>
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<td>3</td>
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</table>

**Comments:**

20. Given the choice, which ski would you take home?

21. Why
Appendix C – Ski Survey Results

The summary of the ski survey from all six of the subjects can be seen in Table 1. The points from each subject were totaled for each of the nine questions.

Table 1: Summary of ski survey results

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<th>Question</th>
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