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Performance Evaluation and Analysis for Kitesurfing

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Abstract. Kitesurfing is an extreme sport that places the participants in situations of risk and potential danger, yet the payoff is an experience that provides exhilaration, challenge, and excitement. Already, many in the sport rely on various technologies to support riders including GPS for tracking position, cameras to record special moments or to refine tricks and techniques. Currently, the sales literature and documentation included with kitesurfing equipment provides only minimal objective guidelines for the proper use including approximate kite shape, surface area in square meters, and windspeed suited for the kite. There are many subjective ratings provided in the sales literature, but the actual performance of the individual shapes and brands is not currently well known. Especially for new riders, this presents a challenge when selecting a new kite or understanding the condition when buying a used kite, which is often the affordable option for beginners. Our interest is to increase the enjoyment and improve safety in the sport by providing more objective measurements of kites using digital technologies. We present a power kite testing system that can be used to evaluate three of the most salient characteristics of a kite while it is being flown including the real time measures of windspeed and the resulting pulling (tensile) forces, resistance to bar movements (bar pressure), and the angle of the kite. We analyze 7 different kites ranging in model year, size, and shape using the testing system. The results are provided as an initial step in the development of two key technologies to improve safety, learning, and coordination for participants in the sport of kitesurfing. Discussion is provided around the future development of kite testing equipment and the further development of technologies for kitesurfing and other extreme sports that can improve safety and performance but also lead to new forms of participation for riders and spectators.

1 Introduction

The sport of kitesurfing and other kite-powered sports is growing rapidly, with steady advancements in materials and safety systems. As with other nylon and cloth-based equipment, over time the materials stretch and the performance characteristics change, affecting the experience the rider has when flying it. Even when kites are new, there is very little objective information that riders have available to understand how a kite will perform other than size and overall shape.

Manufacturers publish their own subjective ratings[9,10,11] which are relative to other kites from their own production line.

As in other extreme sports, digital technologies can enable riders to review and understand their performance, for example, athletes capture moments in a performance session by attaching adventure cameras to their equipment[8]. In board sports, riding speed and jump height can be tracked using sensor input[15]. Research available from the area of kite power generation for sustainable energy indicates that the performance of kites and the forces applied to them can be calculated by modelling and testing to provide reliable and safe control of kites [5,7,12,24]. Considering the risk of bodily injury, it seems worthwhile to explore how technologies can support safe control and understanding of a kite. Some of the characteristics of kite performance that are not well defined include the capabilities of reducing the angle of attack and resulting pull of a kite (depower), amount of force required to control the kite through the control bar (bar pressure), turning speed, and other flight characteristics of kite. How can technology help to understand the performance and characteristics of kites to improve safety and support new experiences for the athlete?

The paper is organized as follows: The following section provides an overview of previous research conducted involving kites followed by the refined research problem. We introduce a testing platform for collection and analysis of performance data, characterizing kitesurfing kites. The prototype measures values relevant to the characterization of kites, which combines sensor input to plot the performance in realtime. Two tensile load cells measure the main load lines and steering lines respectively, while an anemometer measures wind speed. To understand the position of the kite, a combined gyroscope and accelerometer measures the resulting angle of the kite as it flies. We provide results of tests for a range of 7 kites of different sizes, shapes, and year of production. A discussion of the results includes possible explanations for the differences in the gathered data and inights regarding how digital technologies can improve the safety and learning of kitesurfing. The paper concludes with proposed future work joining the current system with existing technologies to support new and enjoyable experiences for riders and spectators.

2 Related Work

The work focused on measuring and exploring kite performance involves the work of traction kite testing, kite control and power generation systems, research into the safety of kitesurfing, and the subjective ratings and categories developed by the kitesurfing brands provided in their marketing materials.

2.1 Traction Kite Testing

Previous research involving traction kite testing for the purpose of identifying differences in kites has been done in one of two ways: using a test rig mounted to a car[22] or by walking the kite in a circular motion[21]. Both methods required testing in no wind conditions to avoid the effects of apparent wind on the results. Testing with the car rig was done by driving the car at an empty beach, flying the kite above the car. The circular testing method required the person testing to walk in a circle, flying the kite in an even bigger circle, thus flying the kite at a speed determined by the pace of the walking person. Both testing methods explored the aerodynamic abilities of traction kites comparing different models to show differences across the years of kite production.

2.2 Kite Control and Power Generation Systems

Since kites were first proposed for wind power generation systems[12], much research has revolved around the applicability of kites in automated control and power generation systems. The theoretical modeling provided in [12] proposes that by using kites, high altitude wind previously unreachable by wind power generation systems can help drive generators on the ground if controlled correctly. Researchers have explored automated control of kites to reduce operating costs and improve efficiency and overall power [7]. In regards to the production of kites, a modeling approach is proposed by [5] and [24]. Breukels[5] proposes a digital toolbox, making it possible to design complex kite models by defining a backbone to create the overall shape and afterwards combine cable, tube, and foil to generate the kite. Zhang[24] explores how the angle of attack of kites affects different forces such as lift, drag applied to the kite and also tether tension. This is both done through theoretical modeling and testing in a wind tunnel.

2.3 Physiological Aspects of Kite Surfing

Studies of physiological demand, comfort, and biomechanical stress within the domain of kite surfing have been performed by [14] and [13] in order to be able to make a realistic assessment of the effects that kite surfing as a physical activity has on the body of the practitioners. The main purpose of these studies is to produce knowledge which should be used to reduce the risk of injury for practitioners as well as development of equipment. They propose that the biomechanical stress on the body when kite surfing is higher than in regular sports and that this contributes to more injuries[14]. They call for studies with the purpose of getting further understanding of biomechanical aspects affecting the muscoskeletal system during kite surfing. The studies called for are: one utilizing sensors to measure pressure between subject and load carrying surfaces and another seeking to map injuries and physical limitations.

In a survey of kite surfing practiotioners, Lundgren et al. seek to find information about what equipment the participants use and why through qualitative (interviews) and quantitative (questionnaires) methods[13]. Results suggest various motivations for the choice of kite shape and type. The SLE (supported leading edge) kites are the most popular dues to the ability for the typical rider to adjust the angle of attack known as sheeting, in order to adjust the power of the kite suitable to the fluctuating wind. An alternative kite shape known as the C-kite does not allow for much differences in sheeting, but was chosen by respondents primarily to support a very specialized trick riding style known as *wake style*, which is associated with powerful acrobatic air movements. Beginners and intermediate riders typically learn on the more robust SLE type of kites for the additional control that is offered.

2.4 Subjective Ratings and Categorization of Kites

The work presented in [5] indicates that kite manufacturers develop kites in a trial and error development process. This suggests that the characteristics of kites used for kitesurfing are based on the experience of testing personnel, and as such, the descriptions for kites are a product of these tests. In fact, there are virtually no quantitative figures other than kite canopy surface area communicated in marketing materials. Manufacturers have a wide range of descriptive words used for describing the flying characteristics of the kites they develop [9,11,10]. CrazyFly Kites[10], for example provides a rating from 0 to 6 to communicate the relative level a particular kite performs including *hangtime, unhooked pop, drift, turning speed, upwind*, etc. Across the various manufacturers, there isn't one consistent categorization or normalized rating system for kites.

3 Research Problem

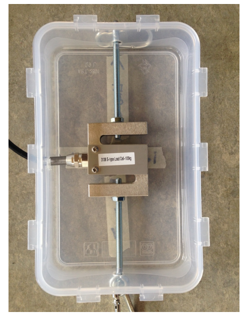
Although there has been substantial research focused on improving the efficiency and performance of power kites there has been surprisingly little research focused on measurement tools to understand the real-time performance characteristics for kitesurfing.

This is problem deserves focus for a few reasons. The subjective ratings and categorizations of kites by the manufacturers leaves the rider with unclear expectations about the actual flying characteristics of the equipment and may lead selection of equipment ill suited to the rider. Beginning riders often use second hand kites, which have been through unknown hours of use leading to stretched lines and canopy fabric that can drastically affect the flight characteristics of a kite. Without a clear idea of the performance when new, it becomes even more difficult to trim and adjust an older kite. Finally, the research focused on the biomechanics and the physiological demands of kite surfing has called for more objective information to be explored in order to reduce the risk of injury for practitioners. So how can we design a kite performance measurement system to objectively measure a kite and how can this be used to improve safety and experience in kitesports?

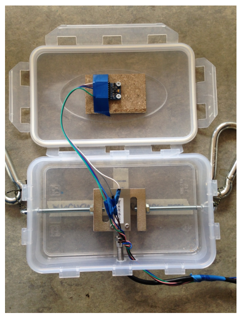
4 Method

We developed a digital testing system that can be used to test modern 4 and 5 line kites, gathering the real-time values for the tensile forces of the main load lines, the bar pressure on the steering lines, the angle of the kite, and the

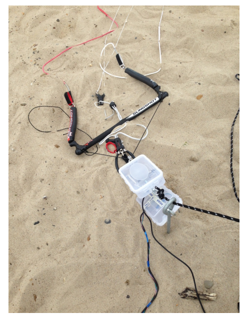
(a) Anemometer



(b) Load cell



(c) Load cell and accelerometer



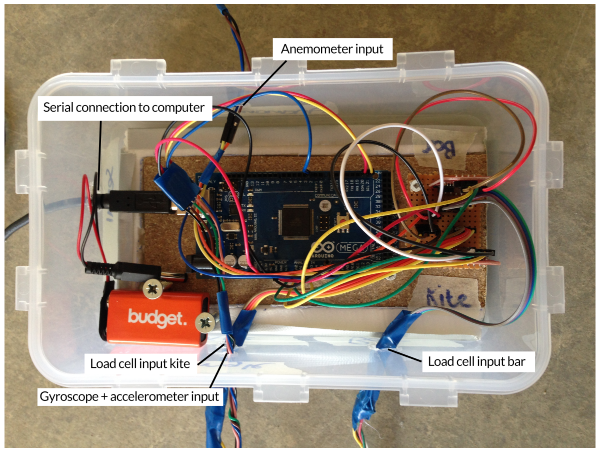
(d) Sensors connected to bar

Fig. 1: The sensors used for the prototype: (a) anemometer, (b) load cell for measuring bar pressure, (c) load cell for measuring kite pressure and accelerometer for measuring angle, and (d) load cells and accelerometer connected to the kite through the bar and chicken loop.

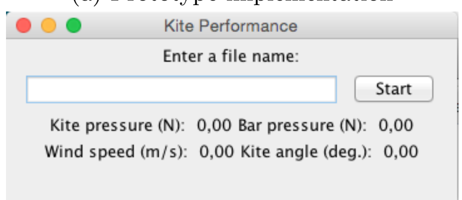
windspeed. These values enable the testing of the kite while tethered to the test station and allows the facilitator to steer the kite through typical movements, which enables the gathering of data and supports the development of a visual representation of a kite's characteristics to compare objectively with other kite models. We evaluated the system with seven different kites from three different manufacturers including Best [9], CrazyFly [10], and Slingshot [20]. Five kites were the SLE type, which typically enable a large depower range including One Slingshot RPM $10m^2$ from 2012, two CrazyFly Sculp $9m^2$ and $12m^2$ from 2015, one Best Nemesis $14m^2$ from 2012, and one Best TS $15m^2$ from 2015. There were two C-kites tested–Slingshot Fuel $9m^2$ and $11m^2$ from 2011.

4.1 Prototype implementation

The prototype used for testing consists of an Arduino Mega 2560 board[3], two tensile s-type load cells rated to 100kg of force [17] connected to the arduino board through an amplifier circuit[4], a combined accelerometer and gyroscope MPU-6050 [2], and an anemometer[1]. One load cell is used for measuring line



(a) Prototype implementation

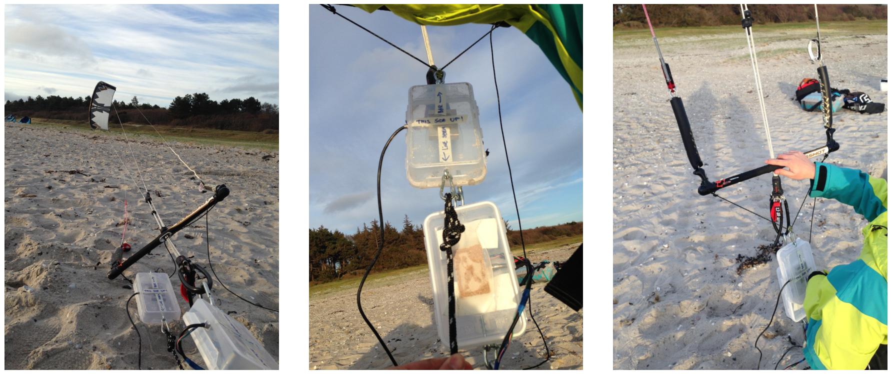


(b) Java program interface

Fig. 2: The two different parts of the prototype: (a) shows the physical prototype excl. sensors, (b) shows the interface of the java program.

tension on the front lines, which transfer the majority of the power from the kite to the rider and an additional load cell measures the tension applied to the steering lines when pulling the bar, i.e. bar pressure. The combined accelerometer and gyroscope circuit is used for measuring the angle of the kite in relation to the ground. Lastly, the anemometer is used for measuring the wind speed and is mounted on a pole at a height of 2.5 metres for more steady and reliable wind speed measurements (figure 1a). To give the sensor equipment the ability to withstand weather and beach conditions, load cells (figure 1b) and the arduino board (figure 3a) are sealed in plastic cases. The accelerometer is mounted on the case with the load cell measuring kite pressure to obtain the most stable angle measurements (figure 1c).

During the setup process of the arduino start up process, the accelerometer must lay still on a flat surface and the load cells should remain untouched for the measurements to be relative to 0 degrees (horizontal) and 0N pull both on the bar and kite as these sensors self-calibrate before the main loop is initiated in the code. The sensors are then connected to the kite through the control bar and the chicken loop, which is the main load bearing connection that normally connects to the rider's harness (figure 1d). To ensure measurements of bar pressure are



(a) The system connected. (b) Bar out. (c) Bar in.

Fig. 3: The system and different states for data collection: (a) the entire system connected, (b) kite being flown with minimal bar pressure at 12 o'clock, and (c) kite being flown with bar pulled in at 12 o'clock.

equally distributed on both steering lines, the load cell being pulled is mounted on a pulley, running on a line from one end of the bar to the other.

The prototype seen in figure 3a supplies a Java program with a realtime data stream of values simultaneously obtained from all sensors. From the interface of this program seen in figure 3c, files consisting of comma separated values (i.e. .csv files) can be named and created. After creation, the files are fed with the data from the serial input stream.

All sensors are calibrated prior to data collection. Load cells are calibrated with known weights to make sure they provide appropriate values. The accelerometer data is filtered by comparing it to the data given by the gyroscope through a complementary filter[6]. Lastly, data from the anemometer is validated by comparing it to the output of a mobile anemometer[23].

4.2 Data Acquisition Protocol

A testing protocol was established for the data collection and consisted of a series of four main steps to be completed in the same way with each kite.

1. Preparation
   (a) Inflate the kite fully
   (b) Connect bar to kite
2. Pre-launch
   (a) Place accelerometer container on a flat surface and calibrate sensors
   (b) Attach kite to trapeze
3. Fly kite at minimum effort
   (a) Launch kite to 12 o'clock
   (b) Connect chicken loop to kite pressure load cell
   (c) Connect bar pressure load cell to bar

(d) Collect 60 seconds data while flying kite at minimum effort
4. Bar pulled all the way in
   (a) Pull bar fully in
   (b) Collect 60 seconds of data with bar pulled all the way in

5 Results

Following the aforementioned data collection protocol we have collected and summarized the data for the seven different kites. Because the wind constantly changes in direction and speed we chose the most stable window of ten seconds in the data collected for two different test cases for each kite: kite flown at minimum effort and kite flown with the bar sheeted in (pulled all the way in). We then calculated averages for the kite pressure (overall pulling force) $\bar{k}$, bar pressure (force required to move the control bar) $\bar{b}$, wind speed $\bar{w}$, and the angle of the kite lines in relation to the ground $\angle line$. The results for kite flown at minimum effort (bar only used to steer kite) is presented in table 1 and the results for kite flown at maximum power (bar pulled all the way in) is presented in table 2.

Kite pressure (see figure 4) is an expression of how much power is generated by a kite at a given wind speed. Figure 4 shows the power range of the kites tested. As expected, we can see that bigger kites generate more power in general. To be able to compare the pull of the different kites we normalize kite pressure to wind speed:

$$kw = \frac{\bar{k}}{\bar{w}}$$

We can also see that the difference between maximum power (bar in) and minimum power to keep the kite flying (bar out) varies a lot between the different kites. This is an expression of the depower capability of a kite. The difference in kw from kite flying at minimum power to maximum power is the depowering capability of the kite:

$$\Delta kw = kw_{max} - kw_{min}$$

Bar pressure (figure 5) describes how hard the kite is to hold at a given wind

Kite (year)	Size (m^2)	Kite (N)	Bar (N)	Wind speed (m/s)	Angle (deg.)
Fuel (2011)	9	142,78	7,23	4,36	81,82
Fuel (2011)	11	148,34	10,13	4,04	81,72
Nemesis (2012)	14	171,53	25,68	4,24	83,89
RPM (2012)	10	121,68	19,66	3,35	82,49
Sculp (2015)	9	105,59	14,68	2,93	78,46
Sculp (2015)	12	148,64	13,19	3,79	82,04
TS (2015)	15	226,98	19,11	4,35	82,42

Table 1: Average of data from measurements taken with kite flown at minimum effort

Kite (year)	Size (m^2)	Kite (N)	Bar (N)	Wind speed (m/s)	Angle (deg.)
Fuel (2011)	9	181,87	72,78	4,18	82,23
Fuel (2011)	11	166,86	64,45	3,62	84,10
Nemesis (2012)	14	316,50	79,00	3,82	86,08
RPM (2012)	10	235,73	97,65	3,91	77,11
Sculp (2015)	9	141,03	49,54	3,19	80,82
Sculp (2015)	12	243,23	87,08	3,86	80,78
TS (2015)	15	433,13	129,77	4,87	82,89

Table 2: Average values of data from measurements taken with kite flown at maximum power.

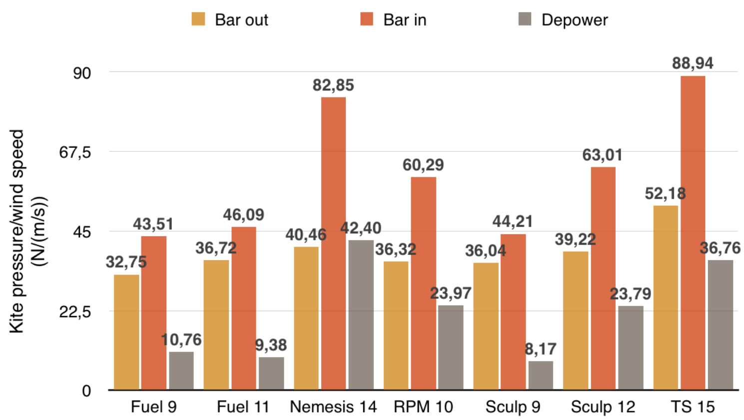


Fig. 4: Average kite pressure of each kite normalized to wind speed.

speed when the bar is pulled all the way in. We can see that in general bar pressure seems to relate well to kite pressure. When looking at figure 5 it is noticeable that the CrazyFly Sculp $12m^2$ and the Slingshot RPM $10m^2$ require more force to hold than the Best Nemesis $14m^2$ even though they are both smaller kites and both generate less power. To evaluate how much force it takes to hold different kites we normalize bar pressure to wind speed:

$$bw = \frac{\bar{b}}{\bar{w}}$$

By normalizing kw to kite size as well we can compare the power range of kites of different sizes (figure 6).

$$kws = \frac{kw}{size}$$

Using kws_{max} and kws_{min} to calculate the difference in power normalized to size we are able to compare the depowering cababilities of kites of different sizes:

$$\Delta kws = kws_{max} - kws_{min}$$

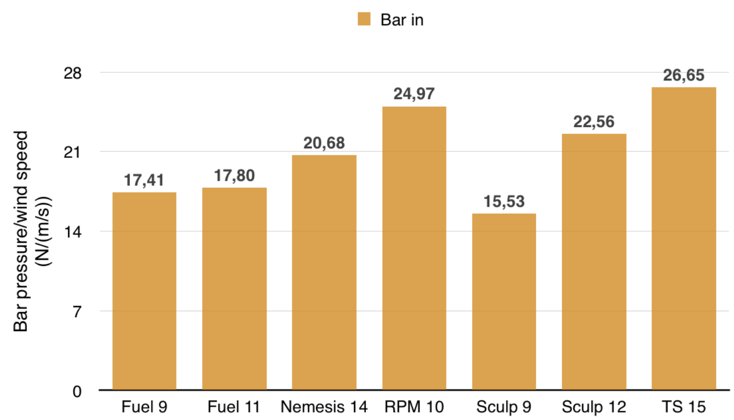


Fig. 5: Average bar pressure of each kite normalized to wind speed.

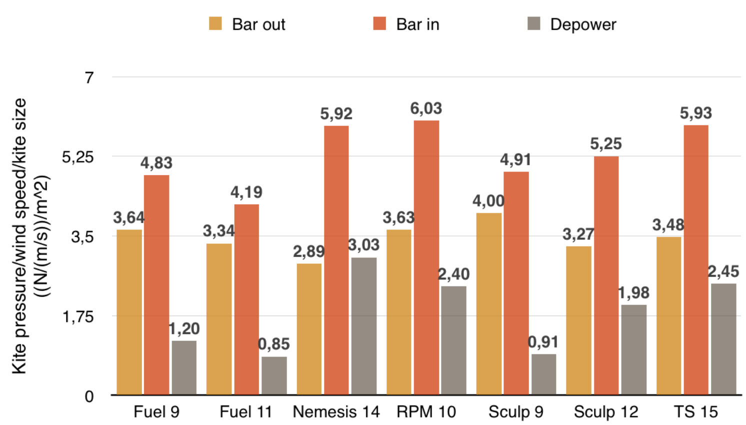


Fig. 6: Data from figure 4 normalized to kite size.

6 Discussion

We have set out to develop a testing system in the hopes of objectively measuring the performance and characteristics of a kite in order to cut through the subjective ratings from manufacturers and to increase the safety in the sport. In this section, we will discuss these initial steps toward building the test system and followed by possible limitations of this work.

6.1 Characteristics of kite models and sizes

Looking at table 4, it becomes apparent that bigger kites produce a more power, which is to be expected. Kites of different types and their depower capabilities were demonstrated in the data. In general, SLE and bow kites have better depower seen in the example of Nemesis $14m^2$, TS $15m^2$, RPM $10m^2$ and Sculp $12m^2$. C-kites lack the depower capabilities of the SLE kite but in some cases, this is desirable. As pointed out in [13], practitioners perfoming the discipline of *wake style* mainly surf with C-kites as these provide stability to perform the tricks associated with this style of surfing. Looking at the data normalized to the size of each kite presented in figure 6, this indication is confirmed. The data for the Sculp $9m^2$ diverges from the trend of SLE kite depower, showing C-kite like stability instead. This might be due to lack of wind for kites of this particular size. It can be discussed whether the results for the fuel $9m^2$ falls into the same category. When looking at the Fuel $11m^2$, the same depower capabilities normalized to size are seen, which could indicate the shape of this particular kite scaling linearly - something not indicated by the results produced by the Sculp kites. To identify more behavioural difference between kites more advanced tests will need to be conducted in a range of wind speed with different settings while measuring tensile forces and the angle of the kite during typical power generating maneuvers.

It is normal for kite manufacturers to present a wind speed range for the different kites and sizes they produce as seen in [9]. Analyzing the data provided by the prototype, a range can also be produced which in turn could aid riders in selecting kites to be safe when surfing, but also provide the best surfing experience. The range depends on a a few factors: kite size, wind speed, rider weight, and depower capabilities of the kite. The range of kites is extended further by providing multiple length options for both steering and main line when these are attached. To be able to fully provide the range of kites, these settings must be all be tested. In regards to safety, the depower capabilities of the kite is a highly influential feature. The more stability provided by kites in regards to kite pressure, the less depower capability and with this, a higher risk of being *overpowered*, i.e. having the kite generate too much kite pressure, thus leaving the rider in danger of not being in control.

It is expected that bar pressure increases as kite pressure increases. Our results show that this is generally true, however, looking at the Slingshot RPM $10m^2$ we can see that it generates more bar pressure than the Best Nemesis 14 m^2 (see figure 5) even though the Nemesis generates more kite pressure (see figure 4). Looking at 2 we can see that the angle of the RPM is a lot lower than that of the nemesis. Kites flying further back in the wind window generate more bar pressure than kites flying at the edge of the wind window (at 90 degrees). This is because as kites fly further back into the wind window, tension on the back lines increases. With the RPM flying so far back in the window, we also expect that specific kite to generate a lot of pressure relative to its size which is exactly what we see in figure 6.

While we have demonstrated that objectively, various kite models differ, it is important to now relate that to the self reported experience of riders using the kites. We discuss more in the Future Work section, however it is important that we now address possible limitations of the current work.

6.2 Possible limitations

To find a relationship between the pull of the kite and the wind speed we use an anemometer[1] measuring the current wind speed at an altitude of approximately 2.5 metres above ground level. In order to get a more precise understanding of the behaviour of a kite in relation to winds aloft it is necessary to measure the wind speed at the height of the kite. This is because the wind at ground level (or just above) and at e.g. 20 metres altitude can, and for the most part will, be very different. It would be worthwhile to consider ways to embed a windspeed sensor at the height of the kite for more accurate measurements.

Another possible limiation of the present work is that we did not test the system on the water with a moving rider. On the water, the anchor point and the kite moves horizontally, which would result in an increase in apparent wind that differs from the true windspeed. The result of this is that the pull of the kite when kitesurfing is going to be greater than what is measured by our prototype. In sailing, the polar diagram[16] can map out the performance at various angles and takes into account the apparent wind (generated from forward movement) however, with kitesurfing, the sail is dynamic and is moved through the sky to generate complex forces of pull from angles that are not simple to model with a static chart. A possible solution to the apparent wind issue is to test with forward movement as in [22], however, the present test is useful because it begins to develop a model of contemporary kites. With the updated electronics available for our system, sensing technologies have been miniaturized enabling the future development of embedded kite technology for real time tracking and feedback.

7 Future work

The research described in this paper is an initial step towards identifying the important characteristics of a kite, however much more needs to be done. To fully understand how different kites behave compared to each other, it is required to do more advanced tests. This includes flying the kite through different maneuvers that are typical for riders to perform while surfing. To fully automate the system, techniques and technology from research provided in [7] could be applied to aid in the development of a computer controlled steering system to test the kite movement and turning speed. There is also a need for standard test procedure to develop something similar to the polar diagram for sails. It is worthwhile to explore possible representations of the results in ways that can be easily compared.

The materials kites are made of stretch and deform over time. The effect this has on the kite performance is an interesting area to explore. It could be possible to provide suggestions for the trim and adjustment of a kite to bring it back closer to the performance when new and could also indicate when a kite is beyond its useful life. As new models of the same kite are sold each year, typically these are marketed as being improved in comparison to older models.

Tests of two kites of similar make and brand but with a different production year could be conducted.

With the building blocks in place, the next step is to use the system on the water to better understand the actual loads and movements of the kite during maneuvers while surfing, and to join this with the kite communication system [19]. Measuring the pull of the kite, the angle of the kite, and the pressure of the bar opens up the possibilities of recording techniques and tricks performed by an expert rider, which could also function as a learning system for others by providing guidance to the rider in real-time when attempting the same trick. We are exploring ways in which the ghost car" metaphor can be adopted using haptic and other modalities to provide a target for riders during the activity, which allows the rider to actively explore ways in which their body position, kite position, speed, and directional control can be adjusted to match the ideal rider [18].

8 Conclusion

In the present paper, we present a prototype that can objectively measure and analyze kites used for the extreme sport kitesurfing. We used this prototype to test seven kites of varying size, shape, and model year. We gathered data by measuring the pulling forces of the kite, the pulling forces on the control bar, the angle of the lines going to the kite relative to the ground, and the wind speed. Our results suggest that the performance of each kite varies depending on the size and overall shape affecting power generated, amount of depower, and stability. This is an important first step towards being able to objectively evaluate kites on the water. This paper calls for the further development of this benchmarking and testing system to provide transparency and knowledge to increase safety and enjoyment for practitioners of the extreme sport of kitesurfing. Among the important work ahead we will explore ways in which this testing system can integrate with other multimodal communication systems to enable rider to rider communication for coordinated performances. We will also consider ways in which spectators could be involved in the sport by visualizing or feeling the sensor data in real-time and thus gain a new appreciation and empathy for athletes in the extreme sport of kitesurfing.

9 Acknowledgements

The contributions of first and second author are equal. We would like to thank the people who supported us by lending us their kites for testing and provided means of transportation.

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