Water Skiing Biomechanics: a study of intermediate skiers

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Water skiing is a sport that approximately 10 million North Americans participate in annually (SGMA International, 2003). Since the first skiers took to the water in 1922 it has developed into a multimillion dollar international sport.

Looking at the current technology of water skiing equipment, it isn't hard to trace its roots. Ralph Samuelson successfully skied on Lake Pepin in Lake City, MN in 1922. He was the first recorded person to water ski. His skis consisted of two pine boards with leather bindings (Winkler, 2009). From this modest beginning came the old style flat bottomed and square tailed skis that were standard for decades. The 1960's were a time of many changes and water skiing was no exception. Affordable high performance boats became readily available, fueling the sport. With this increased power and speed came the demand for skis with improved performance. Manufacturers rose to the challenge, developing the features commonly associated with today's best performance skis including: tapered tail profiles, high wrap bindings, concave bottoms, drop through fins and beveled edges, Figure 1.

All skiers begin their participation in the sport using two skis. Using double skis helps minimize the physical demands of participation and provides a more stable stance. To start a skiing session, skiers assume a seated position in the water. The skier is connected to a tow boat via a rope. As the tow boat accelerates, rope loads increase dramatically and the skier begins to accelerate through the water. As their velocity increases, lift is generated under the skis, lifting the skier up towards the water surface. Rope loads drop throughout this phase of the maneuver. Once planning on the water, the skier is free to turn or cut back and forth behind the boat. Each cut brings about an associated acceleration but requires the skier to generate an increased rope load to power the acceleration.

Intermediate skiers are generally capable of water starting on and skiing on a single (slalom) ski. Using a slalom ski requires more strength, balance and control than is necessary for double skis. Rope loads are also higher but the ability of the skier to cut is much improved and dramatically higher accelerations are possible.

Advanced skiers can attain a high level of proficiency on a slalom ski. Dramatic cuts and accompanying sheets of water sprayed into the air at each turn are the hallmarks of an accomplished skier. Competitive skiers can take this to an additional level by skiing through slalom courses where the skier must ski outside a series of floating marker buoys on opposite sides of the boat. The ability to perform repeated and controlled aggressive cutting with significant accelerations is necessary to be successfully complete a slalom course.

Today with our aging population, there are a large number of individuals who have been active in the sport for years and in some cases decades. Statistics bear this out with the participation demographics showing an average age of 30.8 in the U.S. with an average participation period of 12 years (SGMA International, 2003). With increasing age typically comes increased body mass, decreased overall fitness levels and decreased free time available for participating in the sport. All of these characteristics tend to exacerbate the physical demands the sport places on the participant.

Figure 1 *A representative example of slalom water skis included in this study. The ski at left is a 30 year old, tapered Maherajah 3.5 and includes all the features found on the 5.5 and 8.5 models which were included in the study but not shown here. The centre ski is a currently produced tapered slalom Connelly Concept water ski. This ski is also functionally similar to the HO Monza ski used by one of the skier in this study but not shown here. The ski at right is a current production Maherajah Retro Fastback ski as was used in this study. This ski is longer in length and has a square tail design when compared to the other skis.*

The images at right show several of the features consistently found on high performance water skis. The top right image shows a high wrap style binding. The centre image shows a drop through fin as found on all of the study skis. This image also shows the underside geometry of the tail of a taper tailed ski. The lower image shows the concave bottom and rounded edges typical of those found on all of the skis included in this study.

To capitalize on this demographic reality, ski manufacturers have recently introduced skis that are specifically designed to reduce rope loads and to be generally more forgiving during use. Consistent across the various manufacturers offerings of these skis is an increase in ski surface area to improve lift available from the ski. The Retro Fastback ski, manufactured by Maherajah Water Skis, is an example of this type of ski. This ski differs from its competitor's designs though by its incorporation of a square tail along with the beveled edges, drop through fin and concave bottom features found in competitive skis. Differences in ski configuration are shown in Figure 1. The specifics of the Fastback design are unique to Maherajah Water Skis with the square tail reminiscent of skis popular in the early years of the sport. The reasoning behind this design is to increase lift at the back of the ski during water starts and while skiing thereby reducing the pitch angle of the ski and overall water displacement. Less displaced water should correspond to less force required to pull the skier through the water and correspondingly lower rope loads. Through also incorporating modern performance features into the design the maker is attempting to increase the forgiveness in the ski without sacrificing dynamic performance.

Published research investigating the technology of water skiing has been limited to a simple scientific study reported by Goodrum (2007) where the mathematical factors influencing the sport were reviewed. In contrast, there have been a number of papers published detailing related injuries and statistics including reviews of the published injuries by Roberts 1993 and Hostetler et al, 2005.

Considering the widespread popularity of the sport, and its commercial significance, it is surprising to grasp the absence of any significant research into the sport. This research project was initiated to at least partially address this shortcoming, examine water skiing biomechanics and to specifically quantify the physical demands placed on the novice and intermediate level recreational skier. Of particular interest was to investigate the performance characteristics of the new Retro Fastback water ski and compare it to skis of conventional design. Without previous scientific data to use for comparison, it is expected that the results of this study will form a benchmark for comparison of future research into water skiing.

Methods

The human participation details and written survey used in this study were approved before commencement of the study, by the University of Guelph Ethics Committee. Participants were recruited by advertising for intermediate water skiers interested in participating in a day of skiing research. Ten skiers were recruited in total. One was unable to complete the necessary maneuvers and was removed from the study. Data was collected on two separate days. Two of the skiers were available for both testing days.

Each participant was required to complete a written survey covering their fitness level, current and historical participation rate, weight, etc. The participants were then instrumented and asked to complete a series of skiing maneuvers such as water starting on double and single skis and performing a series of cuts.

Data was collected using both skier based and boat based instrumentation.

Boat speed, direction, location and GPS time was measured using a Global Positioning System (GPS) sensor (model – BG-331RGTGT, Mighty GPS, Toronto, ON) and located on the stern deck of the tow boat. Output of the GPS unit was updated at 1Hz. This unit was connected via a Universal Serial Bus (USB) connection to a NetBook computer (Acer Aspire One ZG5, Acer America Corporation, Mississauga, ON) running a custom data collection program (Labview 8.2, National Instruments Corporation, Austin TX).

Rope load was measured using a custom fabricated axial force transducer built on an aluminum tube using 4 strain gauges (model number - N11-FA-10-120-11, Shinowa Corporation, Tokyo, Japan) organized in a full Wheatstone bridge. The transducer was calibrated using a series of 3, 5 kg masses suspended from the transducer. The force transducer was mounted to the stern of the boat and the ski rope was attached to the aft end of the transducer. Transducer amplification was supplied by a custom built strain gauge amplifier (DiCaprio and Thomason 1989) that was powered by a 15 V power supply (E3630A Agilent Triple Output DC Power Supply, Lexington, MA) connected to a 300 Watt power inverter (Zantrex, Elkhart, IA) and a 12 Volt deep cycle marine battery (Nautilus No. 10-2799-4, Canadian Tire Corporation, Toronto, Canada). Analogue transducer output was input into the data collection computer using an A-D converter (USB-6211, National Instruments Corporation, Austin, TX). Rope load was collected at 10Hz.

Figure 2 *– A test subject shown during a cutting maneuver while using a Maherajah Retro Fastback slalom ski and wearing the instrumented helmet. This subject reached a velocity of 124% of boat velocity, over 70 km per hr / 42 mph when cutting.*

Skier speed, direction and position was measured using a GPS unit (USGlobalSat 20 Channel EM-406a SiRFIII GPS, Chino, CA) that was powered by a standard 9V battery. GPS output was transmitted using a pair of RF transceivers, one mounted on the skier, and one in the boat (434SML-1A, ABACOM WIZ 434 MHz transceivers, ABACOM Technologies, Mississauga,ON). The skier transceiver was powered by a standard 9V battery. The skier instrumentation was wrapped in plastic for waterproofing and placed between the shell and liner of a full cut kayak helmet as visible on Figure 2 (Cascade Helmets, Liverpool, NY). Skier GPS data was received in the boat by the second transceiver, converted to USB format and input into the data collection computer. Skier GPS data sampling was limited to 1Hz.

The tow rope used in this study was a 19.4 m long Airhead rope (Kwik Tek, Denver, CO). The total effective tow rope length including the force transducer, fixing rope and Airhead tow rope was 20 m. The boat used for testing was a 190 Hp, 5.64m, 2006 Horizon manufactured by Four Winns (Cadillac, MI).

The combinations of ski equipment used during the study included double skis with tapered tails, Hydroslide Adult Combo – 1.68 m x 0.15 m (Nash Manufacturing, Fort Worth, TX); double skis where one ski was taper tailed and the second was a Maherajah Retro Fastback Ski – 1.89 m x 0.170 m (Maherajah Water Skis, Kelseyville, CA); slalom skiing on a Fastback ski; and finally slalom skiing on a tapered ski, typical of the type used by advanced recreational and competitive skiers. In this final group 5 different skis were used based on skier preference. These skis included: Maherajah 3.5 – 1.70 m x 0.165 m, Maherajah 5.5 – 1.73 m x 0.163 m and Maherajah 8.5 – 1.81 m x 0.170 m models (Maherajah Water Skis, Kelseyville, CA); Connelly Concept – 1.7 m x 0.172 m (Connelly Skis, Lynnwood, WA); and HO Monza – 1.7 m x 0.175 m (HO skis, Redmond, WA).

Skiers were each required to water start using both double skis formats. After starting each skier was required to ski straight for a period of approximately 30 seconds. Skiers were asked to also water start on both Fastback and tapered slalom skis, and then perform a series of cuts. The order of ski use was ramdomized.

Performance parameters calculated included maximum rope load during water starting, average rope load for straight running, maximum velocity achieved during cuts and the frequency of cutting. For maximum rope load during water starting, the maximum recorded force for each water start event was used for the calculations. Average rope load for straight running was determined for each run using the most data that was available. Maximum cutting velocities were taken as equal to the maximum velocity achieved during the cutting portion of the run. Cutting frequency was calculated using the rope load data from at least 3 consecutive turns and the resulting value reported in terms of cutting period, ie the time required to complete one complete cycle of 2 cuts. Where multiple cuts were available, the cutting frequency was determined using the maximum number of cuts recorded.

Analysis of the resulting data was particularly challenging as the subjects were not all successful at performing the included maneuvers. This combined with the unpredictable nature of the sport transpired to leave the resulting set inconsistent between activities. All reasonable efforts were made to include data generated during the testing sessions. All loading data was normalized by subject mass and skier velocities were normalized to boat velocity to simplify interpretation. Data was assumed to be normally distributed and significance was examined between group results using a single tailed student t-test with significance set at the 0.10 level.

Subject Number	Subject Mass [N]	Fitness (1 – 5)	Skill (1 – 5)	Tapered Slalom Ski used during study
1	935	2.5	3	Maherajah 5.5
2	970	5	3	Maherajah 8.5
3	784/735	5	3	Maherajah 3.5
4	780	5	3	Maherajah 3.5
5	813	3	3	Maherajah 3.5
6	803	5	4	HO Monza
7	735	3	4	Connelly Concept
8	911	4	3	Maherajah 8.5
9	1166	3	3	Maherajah 8.5

Table 1 *- Participant information with fitness and skill assessed by user survey. A level of fitness of 5 corresponding to the ability to jog for 5 km and a skill level of 5 being expert. Skis used by each subject for the taper tailed slalom skiing portion of this study are also listed.*

Results

Nine adult male subjects participated in this study. All had multiple years of water skiing experience, and none were competitive skiers. Subject details are included in Table 1. Skier skill and fitness were assessed in a subjective survey on a scale of 1 to 5 with 5 being expert and fit. Only two of the subjects skied regularly and for the remainder it had been many years since they had participated in the sport.

Weather conditions for the two days of testing were not ideal. Wind and waves were slightly higher than would normally be considered optimal for slalom skiing. All efforts were made to minimize the impact of the environmental conditions on the study results.

Typical rope loads generated during a water start, straight run and cutting are shown in Figure 3. This data was collected for subject 5. The maximum water start rope load, 1213 N (1.49 times body weight) occurring at 13 seconds corresponds to the initial acceleration of the boat and the initiation of forward motion of the skier. During this phase the boat moves forward and the rope becomes taunt. The resulting rope force is the summation of pull by the engine of the boat and the arresting of the boat's inertia.

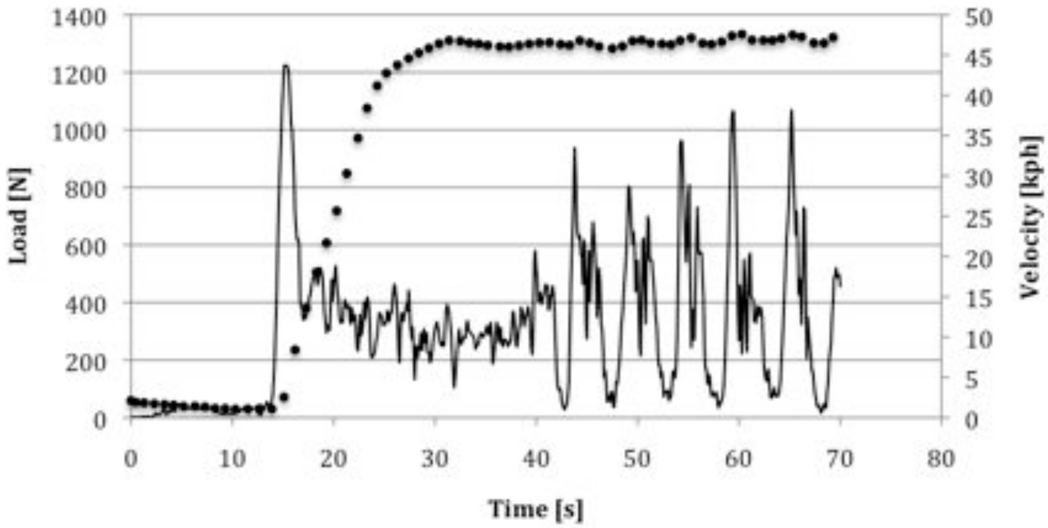

Figure 3 *– Typical data recorded for water starting, straight running and cutting on a Fastback slalom ski. Rope loads (continuous line) and boat velocity (dotted line) are shown.*

Between 20 and 40 seconds the skier was running straight behind the boat and settling in on the ski. Average running rope load calculated from this period was 276 N (0.339 times body weight). After 40 seconds the skier performed 5 cuts. Each cut generated a corresponding reduction in boat velocity. Period of cutting for this skier was 10.6s for the first pair of cuts, 43.8s – 54.4 s, and 10.8 s for the second pair, 54.4s – 65.2s.

The maximum water start rope load recorded during all testing was 1808 N (2.45 x body weight), achieved by subject 7, using a tapered slalom ski.

The average maximum rope loads for each ski combination observed during water starts are shown in Figure 4. These results are normalized by subject body weight. Statistical significance, at the $p \leq 0.10$ level, was found between all of the combinations tested. Average rope loads for double ski starts were 1.48 and 1.62 times body weight for the Fastback/tapered and double tapered starts respectively. Average rope loads during slalom starts were 1.8 times body weight when using the Fastback and 1.97 times body weight when using a tapered slalom ski. Spread of the data was least for double ski water starts and increased for the slalom ski starts. The tapered ski slalom starts required the greatest load generation by the skier and also were the most variable.

Average rope loads measured for running straight behind the boat are shown in Figure 5. The running rope load measured for tapered slalom skiing was found to be significantly greater statistically (at the $p \leq 0.10$ level) than rope loads required for either double skiing with a Fastback ski or slalom skiing with a Fastback ski. No statistically significant difference was seen between double skiing with tapered skis and slalom skiing on a tapered ski. Rope loads measured while using the Fastback ski were roughly equivalent at 0.35 times body weight for both double skiing and slalom skiing. Slalom skiing with a taper tailed ski required greater rope load generation at 0.41 times body weight. This is a

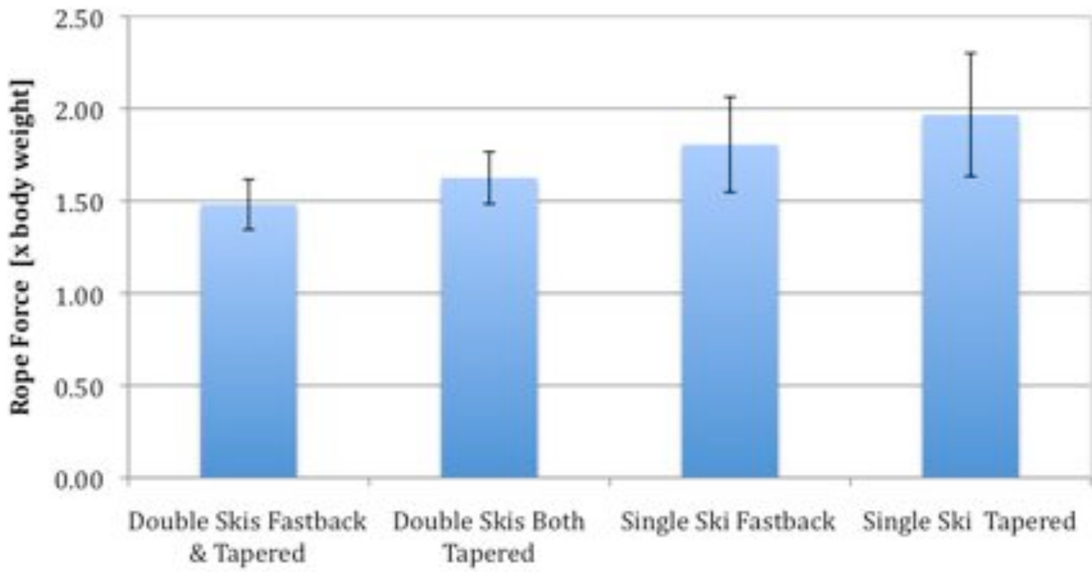

Figure 4 *- Maximum rope loads observed during water starts. Loads were normalized by body weight and averaged (error bars indicate 1 standard deviation).*

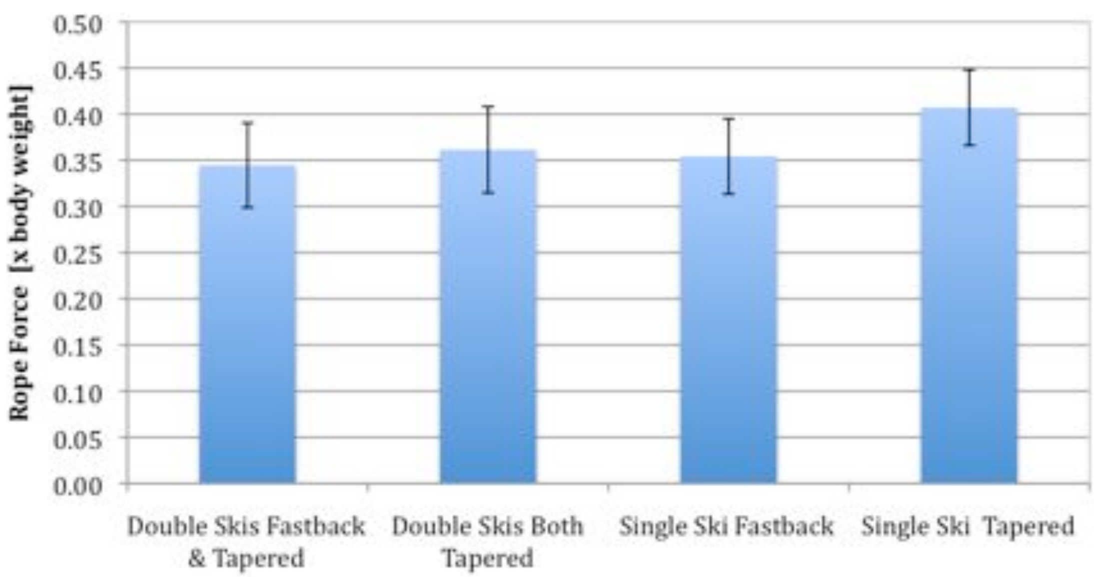

Figure 5 *– Average rope loads while skiing directly behind the boat. Loads were normalized by body weight and averaged (error bars indicate 1 standard deviation).*

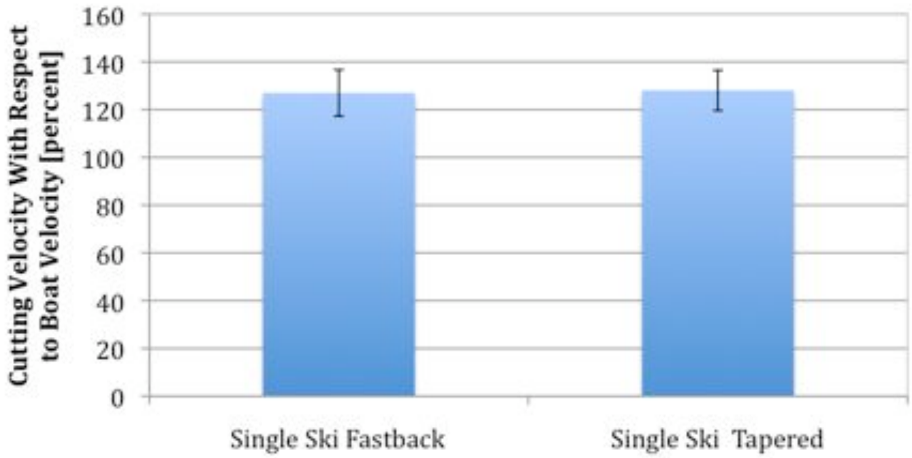

Figure6 *– Average cutting performance of the Fastback and tapered slalom skis were virtually identical. Results were averaged for all cuts made with the Fastback and tapered slalom skis with skiers achieving on average approximately127% of boat speed (error bars indicate 1 standard deviation). Data was compiled from 9 skiers completing a series of cuts with the Fastback and 8 with the tapered slalom skis.*

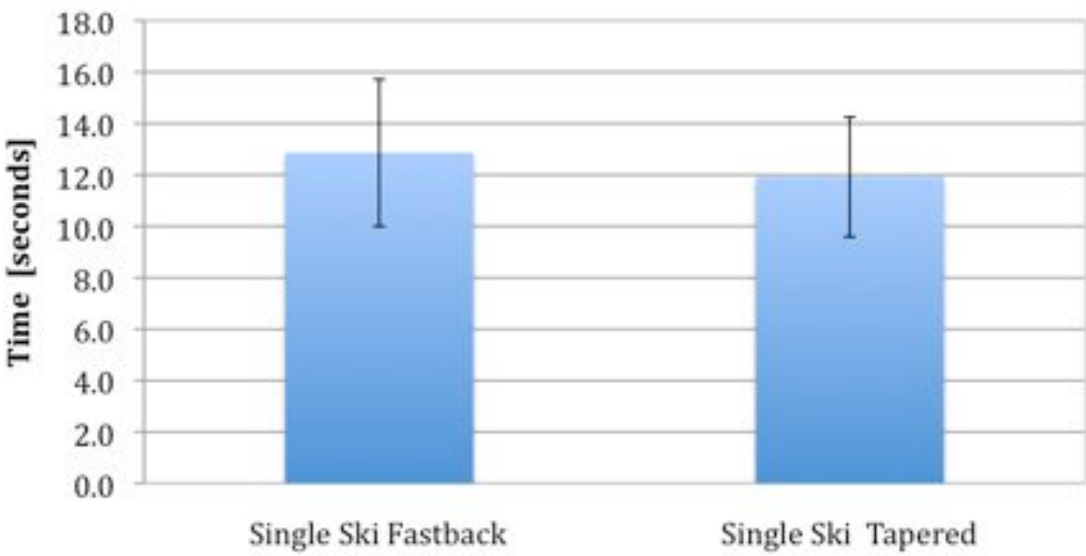

Figure *7 – Average period of cutting achieved using either Fastback or tapered slalom skis was approximately 12 seconds (error bars indicate 1 standard deviation). Cutting period was defined as the time elapsed to complete both a left and right cut.*

17% increase in rope load over the rope loads recorded for Fastback slalom and double skiing.

Cutting performance was only analyzed for the two formats of slalom skiing. In the follow-up survey all the skiers reported that they found the Fastback less “aggressive” on the water when compared to the tapered slalom skis, but our measured data showed that the Fastback accelerated well during cutting maneuvers and on average reached speeds equivalent to those achieved on the tapered slalom skis, 127% of boat velocity, Figure 6. Analysis of the results showed that cutting velocities achieved using slalom tapered and slalom Fastback skis were not significantly different. Interestingly a majority of our skiers achieved higher cutting speeds on the Fastback than on the tapered slalom skis. The highest cutting velocity recorded during the study was 151% of boat speed, for subject 8 using a Fastback slalom ski. The highest recorded cutting velocity recorded for a tapered ski was 141% and was achieved by both subjects 5 and 8.

Average boat velocity for slalom skiing was 54 kph.

The fastest cutting frequency of the study was achieved by subject 7 using a tapered slalom ski. They completed a series of cuts with a period of 8.0 s. The fastest cuts achieved on a Fastback were generated by subject 5 with a cutting period of 8.3 s. On average the cutting period calculated for both ski formats were not significantly different and was numerically equivalent at 12 seconds, Figure 7. Variability in cutting performance was greater on the Fastback slalom ski as indicated by the larger standard deviation shown with the error bar.

Discussion

For anyone who has not attempted to water ski it is difficult to fully appreciate the challenge that water starting represents to the beginning skier. The skier must balance the hydrodynamic forces on the skis, buoyancy of themselves and skis and finally a dynamic rope load. Double ski water starts reduce the challenge of the maneuver by reducing rope loads and simplifying the balance necessary by widening the stance of the skier.

For many novice skiers large water starting rope loads are the first significant challenge that faces them. For most skiers the water starting rope load is also the largest load that will be placed on them during their participation in the sport. For these reasons minimizing water start rope loads is normally considered an asset. Our results indicate that ski choice has an influence on starting rope loads for both slalom and double skis starts. In both instances, rope loads were significantly less when using the wider tailed Fastback ski.

Water start rope load variability results from several different sources. These would include: skier starting technique and balance, skier weight and ski geometry, boat thrust, boat loading, initial boat motion and or rope slack. The first two of these is skier dependent and are most likely responsible for reduced variability in our results calculated for double ski starts. Technique for double ski starts is more consistent than for slalom ski starts.

Most skiers find the sport fatiguing. Aging and occasional skiers are especially affected by the demands of skiing. Of the parameters included in this study, the average running rope load is most closely related to this issue. Water starting loads are typically larger but their total elapsed time is relatively short. In contrast, the running rope load is maintained throughout the duration of skiing. Minimizing this force then has implications on participation times and eventual participant fatigue. Of the skiing formats examined, double skiing and slalom skiing using a Fastback ski required the generation of statistically similar running average rope loads. Tapered slalom skiing required the generation of larger rope loads and would therefore be more fatiguing than the other three alternatives. Our user survey supported this as well. All of the subjects rated the slalom skiing with a taper ski as “hard on the hands” in contrast their average rating for using the slalom Fastback ski was “easy on the hands”.

Running rope load may also play a greater role in dynamic skier performance that is at first obvious. Acceleration of a skier during cutting is driven by the net rope load available to overcome skier inertia. Greater net load translates into greater acceleration. Assuming other factors are unchanged, a skier that requires less force to pull across the water will accelerate faster given an equal net force generated during a cut. Reducing running rope load then allows a greater amount of rope load to be available for accelerating during cuts. This may be a contributing factor in boosting the dynamic performance of the Fastback ski to a level equivalent to the taper slalom skis for the skier group participating in this study.

The water ski manufacturing industry places a great deal of emphasis on slalom ski dynamic performance. The tapered slalom skis included in this study shared virtually identical overall geometric proportions. Differences were primarily in materials, scaling by length and the use of dual high wrap bindings on the Connelly and HO skis. Results achieved by the group of intermediate skiers in this study showed no performance advantage to the use of taper tailed skis over the square tailed, Fastback ski in either cutting velocity achieved (Figure 6) or cutting frequency (Figure 7). A review of this data is especially interesting in the case of subjects 6 and 7 who used their own personal tapered slalom skis. It was anticipated that they would achieve higher levels of performance as indicated by higher cutting velocities when using their own skis than when using the relatively unfamiliar Fastback ski. In both cases their cutting velocities were either equal to or higher on the Fastback ski. An additional fact reinforcing the assertion that there was no performance advantage to the tapered skis was the observation that the fastest cutting velocity achieved in the study was achieved on a Fastback as opposed to a tapered slalom ski. An additional interesting observation from our survey was that a majority of the participants would, given the choice of a ski to take home, choose the Fastback ski over the tapered slalom skis available.

All skiers indicated in the user survey that the Fastback ski was less aggressive and smoother than the tapered skis used in this study. This may also offer a dynamic advantage for skiers at this level. With the improved stability associated with a less aggressive ski, the ski may provide a better platform for the skiers to focus on their cutting technique. This advantage may be reduced with increasing skill level where the dynamic potential of a competitive tapered ski could be more fully exploited by the skier but the results of this study did not include data to support or refute this point.

The participants, equipment and testing details were chosen where possible to be representative of the average intermediate water skiing participant skiing on a typical day. Many alternatives were available in the design of the study. An example would be the use of a standard slalom ski course for evaluating ski performance. While it is recognized that the use of a course may have offered many advantages, the use of a course would not be considered typical for an intermediate skier and was therefore not considered further. In any study of this type, there are a large number of other variables such as weather, boat type, loading and subject fitness, experience and fatigue that will all affect the study results. All efforts were made to minimize their impact, but the results of the study should be viewed with a clear understanding that these parameters will undoubtedly still play a role in the study.

Conclusions

This study has examined the biomechanics and performance of intermediate water skiers. Where possible, all efforts were made to replicate the conditions and experience that an average intermediate skier would encounter while skiing.

Results from this study of intermediate skiers indicate that for this skier group the use of the tapered slalom skis offered no performance advantage over skiing on a Maherajah Water Skis Retro Fastback slalom ski. This is supported by the observed cutting velocities and frequency values that were on average equivalent for both types of equipment. For some skiers in our group, the use of the Fastback offered a performance advantage as indicated by the highest cutting velocity in the study being achieved on a Fastback, and the majority of skiers cutting faster on a Fastback slalom ski. Use of taper slalom skis may offer performance advantages for expert skiers but for the group included in this study, there was no discernable advantage to their use.

Our results also indicate that use of tapered slalom skis for intermediate skiers may actually pose several disadvantages. Tapered slalom ski use required statistically significant larger water start loads and average running loads than skiing with double skis where one was a Fastback ski or slalom skiing on a Fastback ski. The larger loads encountered with tapered slalom skis will have a negative impact on skier fatigue and participation times that could be avoided by using a Fastback ski.

There are many challenges that face water skiers at every level. In general skiers at each level struggle with mastering skills to progress. A beginner may not be able to generate the necessary rope loads to water start and intermediate skiers may find their participation time limited by their own fatigue level. Aging skiers struggle with weight gain and simultaneous strength and endurance loss. For the intermediate skier, our study indicates that the Fastback ski offers performance advantages that may potentially improve their enjoyment of the sport and their overall dynamic performance.

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