Takeoff Forces Transmitted to the Upper Extremity During Water-Skiing

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Abstract

As data were unavailable, this study quantified the forces acting on the upper extremities during water-skiing takeoff in 10 male volunteers (mean age: 28 years). Body weight ranged between 141 and 195 lbs. Low, medium, and full-power takeoffs were used to propel each skier out of the water. Although low-power takeoffs produced significantly less peak force (P=.0004), they yielded a trend toward greater time under load (P=.097). As the data suggest that forces assume roughly one and one-half times body weight, individuals with pre-existing shoulder morbidity may risk exacerbation of their condition.

Water-skiing and the use of personal watercraft (eg, jet skis) have soared in popularity during recent years. For the latter, accident surveillance has noted an increase in the number of watercraft incidents, inclusive of collisions with fixed objects or other watercraft. However, scant literature exists that documents personal injury during waterskiing activities.

Of the few studies available, the preponderance involves deceleration injuries from falls or collisions. Romano et al noted two significant types of deceleration injuries resulting from skier falls: dislocations and lacerations. The former involved the shoulder, hip, and knee, one of which resulted in arterial damage and amputation. The latter included severe laceration to facial structures (noses and mouth) and the urogenital and perianal areas. Others have also noted injury to the urogenital region arising from rapid hydraulic pressurization of the affected body cavity or orifice upon water impact. Additionally, soft-tissue ruptures of the hamstrings, plantaris tendon, rotator cuff, as well as adductor muscle strains, have all been ascribed to skier falls.

Information regarding acceleration-based injury appears less common but nonetheless evident. Several reviews have noted brachial plexus avulsions, injuries to the hand and wrist, hamstring rupture, and clavicle fractures arising from partially submerged skier takeoff to planing at speed. Rope entanglement may also catalyze these injuries.

Few epidemiological studies of water sport injury exist; however, biomechanical data that typify force levels during sport participation do not. For the rehabilitated skier with upper extremity pathology, providing recommendations regarding resumption of sports activities presumes some knowledge of anatomical demands.

As a step toward a better understanding of reinjury risk posed by water-skiing, the force acting on the skier's upper extremities and shoulder girdle as a function of takeoff power was studied. In this regard, it was hypothesized that power is directly related to the forces imposed on the upper extremity.

Materials and Methods

Ten men, with a mean age of 28 years (range: 22-30 years), were recruited for this study. Recruitment complied with the federal requirements for voluntary informed consent and was approved by an institutional review committee. All individuals had previous water-skiing experience. Body weight ranged from 141-195 lbs (mean: 171±14.7 lbs). No volunteer had pre-existing neurologic or musculoskeletal pathology.
Skiing equipment included 185-cm O'Brien water skis (O'Brien International, Redmond, Wash), a 23-m towrope, and a skiing vest. A 1.5 metric ton (displacement) Rinker Model 230 runabout (Rinker Boat Company, Syracuse, Ind) with a 230-horsepower V-8 engine served as the towboat and was capable of speeds >45 mph.

Three discrete towoff power levels were studied: low, medium, and high (full throttle). Level adjustment was based on throttle control stops for low and medium power settings. Setting adjustment for low-power towoff was arbitrary and based on the minimal force required to pull the heaviest skier to planing, the endpoint of data acquisition. High power represented full throttle operation. Medium power was set between these extremes. Testing took place only under ideal conditions—waves <2 ft in Presque Isle Bay, Erie, Pa, August through October 1997.

Two types of skiing styles were evaluated. All individuals participated in two-ski towoffs, starting from a crouched, partially submerged position with ski tips pointed out of the water. Takeoff was complete immediately on stable planing (skier completely out of the water and balanced, ski supporting full body weight). This skiing style represents an elementary maneuver that permitted both novice and accomplished skier participation. Each skier completed all trials at all power levels before the next individual participated.

A subset of five skiers was competent at slalom (one ski) skiing. The data derived from this subset of towoffs were considered pilot information and not subject to rigorous statistical analysis. Starting and ending positions were described previously. Slalom skiing was evaluated once a participant rested from previous two-ski towoff trials. These trials were conducted under full-throttle conditions.

Takeoff force was measured using a calibrated 300-lb load cell (Interface, Scottsdale, Ariz) incorporated into a specially-designed yoke and interposed between the towrope and its attachment cleat at the stern of the boat. The yoke was designed to halve the force level at the load cell, accommodating peak values >300 lbs. Load cell output was registered on a Model P-3500 Strain Indicator (Measurements Group, Raleigh, NC) connected in series to a continuous trace recorder (Heath-Schumegger, Chicago, Ill). Accuracy of the force measurement system was confirmed using calibration weights with output registered in pounds/force. For each participant, measurements were made in triplicate for each of the three levels of towoff power. These values were averaged and recorded.

From the continuous trace record, three parameters were established: 1) average peak force (maximum force generated during takeoff), 2) average relative force (peak force divided by body weight), and 3) average impulse level (integration of force over time).

Raw and weight-corrected data were analyzed using a repeated measures one-way analysis of variance. The alpha level of significance was set at .05. Tukey HSD tests were used for post hoc analysis.

**RESULTS**

Low-power towoffs produced 10%-12% less peak force than medium- or high-power towoffs ($P<.0004$) (Figure 1). Mean force levels were 235.7±34.8, 262.2±33.8, and 268.5±38.7 lbs, respectively. When standardized, these forces represented from 1.4-1.6 times body weight (Figure 2). Low-power towoffs resulted in significantly less force transmission ($P<.0003$).

Impulse levels suggested an inverse relationship to power (Figure 3). Low- and medium-power towoffs produced mean impulse levels of 416.2±115.7 and 401.6±97.5 lbs/second, respectively. By contrast, mean high-power impulse levels were 6%-10% lower (373.9±90.9 lbs/second). This difference approached, but did not attain, statistical significance ($P=.097$). This inverse relationship may reflect the increased time required to achieve planing.

Slalom skiing produced a mean peak force of 338.8±89.1 lbs, a mean relative force of 2.0±0.5 times body weight, and a mean impulse level of 691.4±299.9 lbs/second (data not shown). This increased peak and impulse levels 26% and 85%, respectively, above the corresponding values for two-ski, high-power towoffs.

**DISCUSSION**

Injury prevention requires an appreciation for epidemiological concerns and a fundamental understanding of the forces that act at an anatomical locus or loci. This task is augmented by a
knowledge of pre-existing injury or physical impairment, which lowers the force threshold for injury. Once these factors are comprehended, recommendations can be offered to minimize or eliminate the risk of injury. To exemplify, recent orthopedic reports have suggested that patients with previous knee and hip arthroplasty refrain from participating in water-skiing, which is judged as a high-impact activity similar to football, baseball, hockey, handball, and soccer.11

Our data show that force transmission to the upper extremity for a two-ski takeoff assumes a magnitude of roughly one and one-half times body weight. Aligned with our hypothesis, higher takeoff power produced significantly greater force levels. Slalom skiing exacerbates these forces by an additional 25%. However, absolute magnitude of forces may not be the sole determinant of injury. In this regard, the time under the peak force curve (ie, impulse level) may better represent the more significant concern. An unexpected inverse relationship was found between takeoff power and this parameter. Thus, underpowered watercraft can conceivably expose an individual to more chronic bouts of stress on the upper extremity and shoulder girdle compared with appropriately powered vessels.

Currently, the pathological consequences of peak force or impulse level are unknown. However, the data presented suggest a high level of stress to the shoulder girdle, making participation by individuals with shoulder pathology or prosthesis advisable. This extrapolation from the data is in agreement with the previously cited recommendation that patients with prior hip or knee pathology refrain from waterskiing.11

Our assertion that force is transmitted from the towrope, through the entire upper extremity, and focused within the shoulder girdle is reasonable from a biomechanical perspective. Prior to takeoff, the towrope is pulled taut, causing the upper arms to assume full extension with roughly 40° of flexion at the shoulder. Segment weights for the upper arm, forearm, and hand are small compared to the forces in the towrope and further minimized by buoyancy. Assuming that segment accelerations are small, little force attenuation would be expected through the upper extremities and most of the force would be borne by the shoulder girdle.

Limitations of the data should be noted. The coefficient of variation for peak force data was 15%, suggestive of a reasonable precision level. However, impulse data were more highly variable, producing an overall 25% coefficient of variation. This variability was a function of diverse skier experience, as well as the methodology for deriving impulse data.

With respect to the latter, time values were read from the force trace and were not independently measured with a timing device. This impulse data is presumptive and awaits further studies for confirmation or clarification.

**CONCLUSION**

Based on a moderately powered runabout, peak takeoff forces transmitted through a towline during water-skiing were up to 1.6 times body weight. Although force transmission was related to boat power output, the latter was inversely related to impulse level (time-to-attain planning × force). Thus, under-
powered watercraft may subject a water-skier to greater cumulative stress. Overall, this activity may not be advisable for individuals with pre-existing arm or shoulder injury, as in the case of anterior shoulder instability.

REFERENCES

EDITORIAL DISCUSSION
ORTHOPEDICS: Could any change in the maneuvers potentially decrease the forces?
Keverline et al: Our study specifically addressed a standard skiing position during either one- or two-ski takeoffs. Although we did not vary maneuvers from these standardized positions, at least three factors affect peak force levels and time under load: surface area of the skis, skier experience, and skier body weight.

Slalom skiing increased peak force by 25% over two-ski takeoffs, suggesting that ski surface area contributes to the "lift" needed to overcome gravitational effects. We also observed that experienced skiers required less time to come out of the water. Although not necessarily affecting peak load, this factor favorably impacted impulse levels (time-under-load). Finally, skier body weight dictates the amount of power required to efficiently pull the skier to planing. Power efficiency in this regard can be construed as the amount of propulsion needed to minimize both peak force and time-under-load.

It should also be recognized that the posterior shoulder musculature help counteract translation of the humeral head within the glenoid during activities that generate anterior-directed forces. This musculature includes the rotator cuff, deltoid, latissimus, and to a lesser extent, the long head of the biceps. Appropriate strength conditioning of these muscles would help stabilize the joint during peak loading and reduce the risk of injury.