# AN UNDERWATER IMPACT BIOMECHANICS STUDY TO EVALUATE A BOAT MOTOR CAGE-TYPE PROPELLER GUARD AS A PROTECTIVE DEVICE

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## ABSTRACT

This research was conducted to describe and quantify the nature and extent of impact injuries inflicted on a swimmer's leg when struck by a particular cage-type propeller guard on a boat outboard motor. A specific objective was to determine a threshold velocity above which the injury would be considered to be sufficiently severe enough to result in loss of leg function. An outboard motor fitted with a cage-type prop guard was towed at various speeds on a platform attached to a centrifuge arm. The prop guard was impacted at decreasing velocities onto a series of embalmed human cadaver legs positioned stationary underwater and connected to the upper-body components of a Hybrid III test dummy. Measurements were made of: 1) the velocity of the impactor as it struck the cadaver legs, 2) the external response of the legs and attached Hybrid III components (via high-speed motion pictures and video), and 3) acceleration and force (for some of the tests). Post-impact analysis of the test legs included detailed radiographs, careful dissection, and evaluation of fractures to the tibia and fibula. Specific tissue responses evaluated were bone fracture and fragmentation patterns. Six out of seven of the legs tested resulted in comminuted fractures so severe that loss of leg function would be expected. The seventh impact, at the lowest velocity of 10.4 mph (16.7 km/h), resulted in a transverse fracture from which full recovery would be likely. As the next lowest velocity of impact was 13.6 mph (21.9 km/h), it was concluded that for the loading condition and population studied in this series of tests, the specific prop-guard cage would not be an effective device for preventing severe leg injury at boat velocities greater than or equal to about 13 mph (21 km/h).

ALTHOUGH THERE ARE NUMEROUS PATENTS of different propeller guards that have been filed in the United States dating back to the 1930's, no major marine engine manufacturer currently offers for sale a guard for propellers that is intended to protect people in the water. Most recreational power boats are propeller driven by an outboard motor. Design efforts directed towards alleviating or reducing propeller injuries have involved the development of rigid metal devices that surround the propeller. They are usually ring- or cage-shaped and are designed to prevent the people in the water from making contact with the propeller blades. The United States Coast Guard and various outboard motor manufacturers have tried to understand the feasibility and effectiveness of such devices.

The reluctancy to use these guards involve many issues that have become quite controversial. An issue of primary importance is protection. How do resultant injuries from contact with modern-day guard designs compare to that of direct propeller contact? Other issues of concern include, but are not limited to, hydrodynamic effects, guard durability, and consumer acceptance.

This paper only addresses the issue of injury severity and guard effectiveness. A specific cage-type guard was used for this study, and it has been reported to be one of the "safest" modern-day designs of the many that have been developed.

The issues of incidence and severity of propeller injuries, feasibility of injury countermeasures, and regulatory and litigation efforts have been extensively discussed in various forums, including the scientific literature, tort litigation, and federal hearings. Even a special subcommittee of The United States Coast Guard's National Boating Safety Advisory Council was appointed to investigate such issues. A 50-page document authored by Baker et al (1992) from Jon S. Vernick and Associates, The Johns Hopkins University Injury Prevention Center, and the Institute for Injury Reduction addressed many of these issues in a report in which the purpose was to collect and summarize existing studies regarding motorboat propeller injuries.

Agreement among various groups does not exist with respect to propeller injury incidence and guard effectiveness. The US Coast Guard Boating Statistics Data over the past 20 years show only about 100 people per year are injured or killed from boat or propeller strikes. Other groups have reported higher incidence rates. Whether the incidence is low or high the question still remains involving the effectiveness of injury-mitigating devices (i.e. guards). The remainder of these introductory remarks are intended to briefly discuss some papers that address the injury issue associated with outboard motor propeller strikes, as well as introduce the work reported on in this paper.

Sleight (1974) reported on six patients injured by high-speed boat propellers. Four of the six cases involved strikes to the lower extremity and two of those resulted in amputations.

Mann (1980) discussed 32 cases of propeller injuries with both traumatic and therapeutic amputations. Bacterial contamination was a problem in the majority of cases. The most common injuries associated with being struck by a boat are severe lacerations. He reported that there were 1,761 injuries from 6,529 reported boating accidents in the United States in 1978. Ninety-two were caused by propellers.

According to Kutarski (1989), outboard motor propellers can inflict severe, often fatal, injuries. His paper quotes Coast Guard figures in the US: approximately 2,500 to 3,000 people are injuried annually in boating accidents and 1,000 to 1,400 are killed. It is estimated that only 5-10% of reportable nonfatal accidents actually are reported to the authorities. Kutarski's review of the literature of case studies involving small propeller wounds found an overall fatality rate and major amputation rate of about 15%.

Gayle et al (1991) reported on lower extremity replantation, in which one case involved a boat outboard motor strike to a 6-year old boy causing a severe left open midshaft comminuted tibial fracture. The posterior tibial neurovascular bundle was intact. The right leg was extensively crushed with near-complete amputation and its posterior tibial nerve was intact, but vessels and anterior neurovascular bundle were divided. Some bone was missing and, after repeated efforts to save the right leg over the course of 15 days, it had to be surgically amputated below the knee.

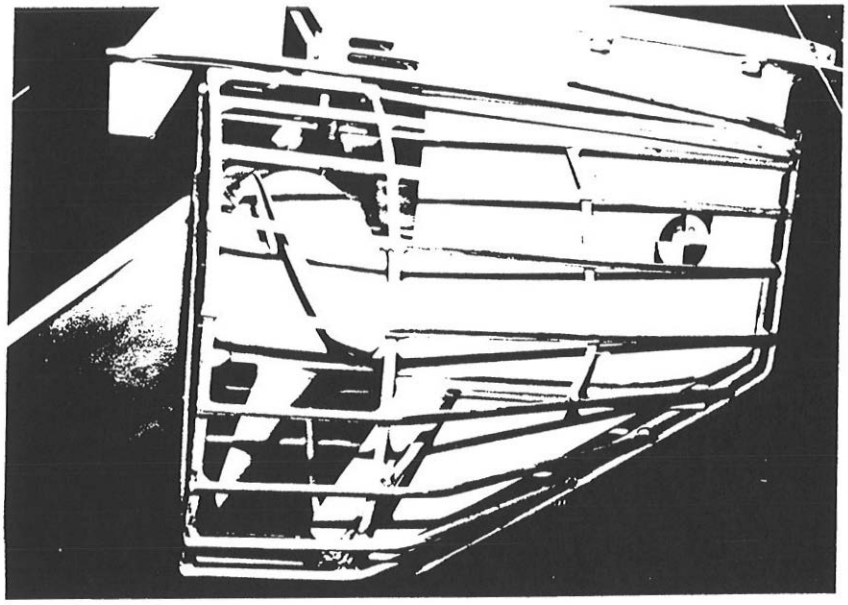
Gomez et al (1991) thoroughly reviewed the topic of propeller injuries and stated that they are the most devastating of all nautical injuries, listing traumatic amputation of limbs and propeller strikes to the skull as potentially lethal. Gomez mentioned a survey of orthopaedists regarding prop injuries that documented 195 injuries from 1979 to 1983 in the US. Also discussed was a 1978 report by the Department of Transportation (DOT) and The US Coast Guard titled "Struck by Propeller." The investigators from the DOT and the Coast Guard concluded that viable approaches to reducing propeller accidents are using propeller guards and implementing massive education/training. However, almost ten years later in 1987, the same institution stated that "no further research on mechanical devices should be funded until the new data are analyzed and the problem (propeller injuries) is properly defined."

In 1994, Hartgarten et al (1994) wrote about propeller injuries in Wisconsin from 1987 to 1989. They reported on 3 fatalities and 14 nonfatalities. Lower extremities were involved in 71% of the nonfatal cases. The authors discussed the benefits of propeller guards but did not list any research data to support the claims. An interesting remark within the paper was that manufacturers are reluctant to study propeller guards. This is interesting because a couple of US outboard motor manufacturers have been the primary organizations involved in a significant amount of the research and development that has been completed with regard to the design and feasibility of propeller guards.

The tests for the reseach reported on in this paper were performed at the Center for Research in Special Environments at the State University of New York (SUNY) in Buffalo, New York, to take advantage of an existing facility conducive to underwater impact tests (Kress, 1996).

The facility includes an 8-foot (2.4-m) deep toroidal water tank that surrounds a centrifuge which has a 31.7-foot (9.7-m) arm. The purpose of the tests was to study the effects of a specific cage-type guard on injury severity to the human leg. The cage-type guard, shown in Figure 1, is made of 5/16 inch (.9525 cm) diameter steel wire rods welded together in such a fashion that the "impact" end forms a wedge that makes a transition to a cylindrical section covering the propeller.

**Figure 1 - Photograph of cage-type guard mounted on propeller in which the forward direction of travel for the boat is to the right**



A specific objective was to determine a threshold velocity above which the injury would be considered sufficiently severe to result in loss of leg function. Our general meaning for "loss-of-leg-function" is that the injury would be so severe that the individual would experience permanent disablement. This injury severity, then would correspond to AIS3 and AIS4 of the "1990 Abbreviated Injury Scale" of the Association for the Advancement of Automotive Medicine (AAAM). In addition, the AAAM has defined a "descriptive" impairment scale that supplements the numerical ratings. Our definition of loss of leg function would be expected to be described as permanent "mobility," "cosmetic," and "sensory" impairment.

## METHODOLOGY

A total of eight embalmed human cadaver legs (sectioned at mid-thigh region and connected to the upper-body components of a Hybrid III dummy) were used for the study. Ball-and-socket metal "hip joints" were the connective links between the cadaver legs and the Hybrid III components. The joints were connected to the femurs of each leg by the use of surgical cement and then attached to the Hybrid III in a manner such that the Hybrid remained "waterproofed." The legs were impacted with the prop-guarded motor towed at various speeds beginning at 21.0 mph (33.8 km/h). The speed was systematically decreased until a "threshold" velocity was determined above which injury is so severe that loss of leg function would result. Table 1 shows the conditions for all the tests. The average age at time of death for the specimens was approximately 75 years. All cadavers were embalmed within a couple of days after death; specifically, the information with regard to embalmment before testing is as follows: three legs - three years; two legs - four years; two legs - six years; two legs - eleven years; and one leg - one year.

**Table 1 - Test conditions and resultant fractures**

| Test # | Impactor | Velocity mph (km/h) | Accelerometer | Fracture Description |
|---|---|---|---|---|
| L1 | CGM[1] | 21.0 (33.8) | No | Comminution[2] |
| L2 | CGM | 21.0 (33.8) | No | Comminution |
| L3 | CGM | 17.2 (27.7) | No | Comminution |
| L4 | CGM | 17.2 (27.7) | Yes | Comminution |
| L5 | CGM | 13.6 (21.9) | Yes | Comminution |
| L6 | CGM | 13.6 (21.9) | Yes | Comminution |
| L7 | CGM | 10.4 (16.7) | Yes | Transverse[3] |
| L8[4] | PIPE | 17.2 (27.7) | Yes | Non-applicable |
| L8M[5] | PIPE | 17.2 (27.7) | Yes | Non-applicable |

Notes: [1]CGM: Cage-Guarded Motor
[2]Comminution: Comminution fractures of the proximal tibia and fibula
[3]Transverse: Transverse fractures of the proximal tibia and fibula
[4]L8: This test included a force transducer.
[5]L8M: This test was a second impact to the leg used in test L8. Test conditions were the same, except that fracture had already occurred from test L8. The purpose of this special test was to independently measure the forces required to accelerate the mass without including the force to fracture the bone.

For seven of the eight legs tested in Buffalo the following were the fixed conditions:

1) impactor: cage-type prop guard (see Figure 1),
2) object impacted: embalmed human cadaver leg connected to Hybrid III torso,
3) position of leg: horizontal to water surface and completely submerged,
4) impact location: proximal one-third of tibia, and
5) impact direction: anterior-to-posterior.

Accelerometers were placed inside four of the seven legs near the point of attachment to the Hybrid III components. This allowed the researchers to obtain acceleration data to be obtained for possible future empirical correlations. A special test was required to relate the acceleration data to the applied force. For this special test, the impactor was a pipe structure previously used during in-air tests at The University of Tennessee laboratory. This pipe structure included a transducer for direct measurement of the force.

Photographs were made of the legs before and after the tests, and high-speed motion pictures were made of the impacts. X-rays were taken of the legs prior to and after testing. Extensive dissection work was performed to evaluate the nature and extent of injury.

## INSTRUMENTATION AND SPECIMEN EVALUATION

Each leg was characterized before and after impact by utilizing x-rays, still photography, and various anthropometric measurements. Post-impact evaluation included dissection with particular attention directed toward bone fracture and fragmentation.

The instrumentation system employed during the impacts provided a time base, impactor position and velocity, and the external leg response to the impact (via high-speed photography).

Accelerometers and a force transducer were used as discussed in the methodology section of this report. The data acquisition system that recorded the signals was a Hewlett Packard 3562A analyzer.

Nominal impact velocities were established by presetting the values on a PC computer that was programmed to generate an analog control voltage. After the test series, a special study was conducted by SUNY to calibrate the speed of impact as preset by the computerized control system. The results showed that the maximum difference in the measured versus preset speed was about 0.24% and that a typical value was about 0.04%. It was concluded that the actual speeds of the impacts were within a fraction of a percent of the preset values.

## RESULTS

The results for all the tests are summarized in Table 1 (previous page). Examination of the post-test x-rays revealed that velocities at 13.6 mph (21.9 km/h) and higher all produced comminuted fractures of both the tibia and fibula that were judged to be severe enough that loss of leg function would have resulted. The post test x-ray of the leg impacted at 10.4 mph (16.7 km/h) revealed less severe transverse fractures of the tibia and fibula for which it was judged that loss of leg function would not have resulted. Consequently, the threshold velocity is judged to fall within the range of 10.4 mph (16.7 km/h) to 13.6 mph (21.9 km/h). Because of the small number of sample specimens, additional tests are needed to provide a statistically justifiable technical basis for this result.

The observed comminuted fractures have a high probability of resulting in a great many complications, some directly related to the fracture itself, and others attributable to subsequent effects. These effect as discussed by Pike (1990) may include: infection; bone shortening; avascular necrosis; tears and lacerations to nearby vasculature (arteries, veins, and/or capillaries); injury to nerves and connective tissue and post-traumatic arthritis of joints; joint disruption; microembolism (also referred to as fat embolism); myositis and myositis ossificans; immobilization which could cause complications such as pressure sores and even pneumonia; compartment syndromes which can result in ischemia, hypoxia and anoxia which in turn can produce muscle necrosis and irreversible nerve damage.

The vascular and neurological damage expected for the extent of bone damage was not observed during post-test dissection of the legs. It is believed that this lack of effect was due to the "leather-like" condition of the soft tissue as a result of long-term storage and fixation. Unfortunately, most of the cadaver legs available for this study were all embalmed at various times ranging from about three to eleven years before the tests were conducted. During this time, the tissue had changed to the point that soft tissue damage could only be inferred from the extent of bone damage. Two additional tests to confirm this were conducted in-air at The University of Tennessee (UT) laboratory using legs from the same population in a similarly deteriorated state at test conditions that are known from prior testing to produce extensive vascular and neurological damage to "fresher" legs. Results support the above conjecture that extensive vascular and neurological damage should have occurred. Both legs were impacted at 17 mph (27 km/h) using a special "pipe impactor" at the UT laboratory. Each of these tests resulted in comminuted type fractures of such extent that the soft tissue damage could have been expected to be extensive based on similar tests with "fresher" embalmed legs. Similar to the underwater tests, however, no such extensive soft tissue damage was observed. This, then, confirms the speculation that the lack of damage in the water tests was a result of the fixation and long-term storage conditions.

To supplement this finding, additional measurements were made of the modulus of elasticity of the muscle tissue of the specimens. The measured value was approximately an order of magnitude higher than that for "fresh" muscle.

Also, important to note is the fact that nerve damage is not always detectable upon dissection examination. This is because stretching can cause severe injury that may not be apparent in cadaveric specimens.

Since the soft tissue was a crude representation of the soft tissue of a "fresher" leg, speculation may arise with respect to the bone's condition. The bones appeared to be normal and comparable to those of a fresher population. To support our claim that long-term storage and fixation effects did not affect the bones adversely as they did the soft tissue, a direct comparison was made between the average cortex thickness and breaking strength of the tibias in this study to that of a "fresher" population of tibias from a previous study (Japan Automobile Manufacturers Association project data from 1989 Annual Report produced by The University of Tennessee). See Table 2 for this comparison.

**Table 2 - Comparison of bone characteristics**

| | Average Cortex Thickness (mm) | Breaking Strength (N) |
|---|---|---|
| Tibias in LI - L8 legs (in-water tests) | 6.64 | 2,667* |
| Tibias from "fresher" leg population (in-air test) | 5.75 | 2,401 |

*This is not an average value. It is the breaking strength of the tibia from leg L8 only.

The 6.64 mm average cortex thickness of the tibias from this study is a reasonable average compared to the "fresher" population of tibias. It actually is an indicator of stronger bones since 6.64 mm is greater than 5.75 mm. The special test (introduced in the methodology section of this paper) provides valuable data to establish normality of this population of bones also, even though the soft tissue is so different. Leg L8's average tibial cortex thickness was 7.56 mm. The peak force value measured during impact of test L8 was approximately 5,000 N and the peak force measured from test L8M was 2,333 N. Therefore, the approximate breaking strength, $F_{water}$, of the tibia is equal to:

$$F_{water} = 5{,}000 \text{ N} - 2{,}333 \text{ N} = 2{,}667 \text{ N}.$$

Note that the breaking strength values in Table 2 are comparable. The breaking strength in water, $F_{water}$, was only 266 N greater than that in air $F_{air}$. The cortex thickness of L8, which is greater than that of the "fresher" leg average value, could account for the slight difference.

The long-term storage and fixation apparently did not affect the bone strength adversely as it did the soft tissue. Therefore, the resultant fracture data are considered to be valid and representative.

## DISCUSSION

As shown in Table 1, six out of seven of the resultant fractures from the leg tests were comminuted with multiple fragmentation. These fractures or resultant injuries are considered to be "conservative" (or less severe) than what would be expected in "real-life" situations, because:

1) during the tests, all of the legs pulled loose at the hip connection limiting the inertial constraints imposed by the upper-body Hybrid III parts,
2) the direction of impact of the tibia is the "toughest" direction of the bone for a transverse load, and
3) the proximal region of the tibia is stronger than the midshaft and distal areas.

It is the judgment of the researchers that, for the loading condition and population studied in this project, the prop-guarded cage was not effective in preventing extensive injury to the leg at boat velocities greater than or equal to 13.6 mph. Above this speed, the observed damage was so severe that loss of leg function would be expected.

Six out of the seven cadaver legs tested were pulled loose at the hip connection to the test dummy. Although attachment of the cadaver leg to the test dummy may have different hip failure characteristics than for an intact cadaver, the delivered forces are expected to be comparable. There may be a need to examine post-impact forces experienced by the hip with and without the cage-type guard. We speculate that more severe hip injuries would occur more often when a cage-type guard is used.

It may be of interest to discuss the relationship of injury to that of the geometry (or size) of the leading edge of the impactor (i.e. the edge of the cage vs. the edge of the strut, skeg or propeller). For simplicity, the cage impacting surface will be referred to as "blunt" and the strut, skeg and propeller edges as "fine." The blunt leading edge has a larger impacting surface area than the fine leading edge. Injuries produced from a fine leading edge are usually associated with more localized damage. As speed increases, however, to around 13 mph (21 km/h) and above (such as those of the six tests referred to in this paper) localized damage can be just as severe from a blunt impact and can often be worse (e.g., could be more difficult to surgically repair). In addition to causing severe localized damage, the blunt impactor can cause increased hip injury, flailing, and whole-body damage as opposed to the fine impactor.

At speeds of about 13 mph (21 km/h) and above it would be expected that both "impactors" (with and without the cage-type guard) would cause damage so severe that loss of leg function would result which may require amputation. If traumatic amputation on impact does no occur, then the resulting motion of the two impacting objects (boat and human) will be in the direction of the boat's travel and will be at about the boat's impact velocity. The inertial restraint imposed by the mass of the foot and the lower leg allows for a "wrapping" action of the leg around the impactor causing energy transfer to the rest of the body. Severe hip damage and other injuries are expected to result from this dynamic action. It is also expected that, for impact conditions as in these tests, the caged motor would exacerbate the "wrapping around" or grasping effect. Because of this, at speeds of about 13 mph (21 km/h) and above, resultant real-life impact injuries from a caged-guard impact are likely to lead to impairment that would be equivalent to that of amputation to the leg or other serious whole-body injuries. Succinctly, if the energy transfer is not local as in amputation then it is sent elsewhere to do other damage probably generating an increase in overall bodily injury of a more serious nature.

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