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Does Military High-speed Boat Slamming Cause Severe Injuries and Disability?

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Abstract

Background Many operators of professional high-speed boats suffer severe, acute, and permanent injuries caused by slamming-induced hull impacts. As the number of professional high-speed boats and their speed capabilities increase, operators are reporting increasing numbers and severity of injuries. However, the actual incidence rate of acute injuries and the prevalence of chronic musculoskeletal disorders are still unknown.

Questions/purposes We sought to investigate, among professional high-speed boat operators, (1) the self-reported incidence rate of impact-induced injuries, (2) the most common types of injuries or injury locations, (3) what impact characteristics were reported, and (4) the prevalence of self-reported sick leave, disability, and medical or orthopaedic treatment.

Methods This study was an internet-based survey among retired military high-speed boat operators. The survey was given to members of the Combatant Craft Crewman Association online user group (360 members). Participants answered questions on demographics, service branch, service years and capacity, boat type, types of events, injury location, severity, pain, disability, and need for treatment. Values are presented as the mean ± SD and proportions. Incidence rates are presented as injuries per person-year. A total of 214

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members of the Combatant Craft Crewman Association participated in the survey (213 men, mean age 50 ± 9 years, mean BMI 29 ± 4 kg/m^2). A total of 59% (214 of 360) of those we surveyed provided responses; all provided complete survey responses.

Results The self-reported incidence rate of impact-induced injuries was 1.1 injuries per person-year served onboard. A total of 32% (775 of 2460) of respondents reported injuries that affected the back, and 21% (509 of 2460) reported injuries that affected the neck. Among those who responded, 33% (70 of 214) reported loss of consciousness onboard, and 70% (149 of 214) reported having experienced impaired capacity to perform their job onboard because of impact exposure. A total of 49% (889 of 1827) of the reported injuries were attributed to impacts containing lateral forces, 18% (333 of 1827) to frontal impacts, and 12% (218 of 1827) were attributed to purely vertical impacts. Finally, 67% (144 of 214) of respondents reported at least one occasion of sick leave from training or missions. Seventy-two percent (155 of 214) applied for a Veterans Affairs disability rating, and 68% (105 of 155) of these had a rating of 50% or higher. Additionally, 39% (84 of 214) reported having had surgery during active duty, and 34% (72 of 214) reported surgery after leaving active service.

Conclusion The results suggest that in the investigated military population, exposure to slamming-induced impacts onboard high-speed boats may cause more injuries than previously reported. Most reported injuries are musculoskeletal, but the high number of reported slamming-induced events of unconsciousness is concerning.

Level of Evidence Level IV, prognostic study.

Introduction

During the past two decades, an increasing number of case series on injuries onboard high-speed boats have been published [1, 5, 6, 19, 26, 28]. This is especially true for military high-speed boat operators. A study among 84 active-duty operators and crew onboard French Special Forces high-speed boats found that 67% (56 of 84) had experienced at least one injury related to a boat ride during the past 12 months, and 38% (32 of 84) of these active-duty operators took pain medications regularly [16].

Exposure to a potentially injurious whole-body impact is not limited to military special-forces boat operators. An increasing number of powerful high-speed boats are in use by sea rescue institutions, coast guards, border patrols, customs teams, law enforcement, and a variety of offshore industries including wind farming, as well as tourist boat companies and leisure boat owners [1, 3]. Potentially injurious whole-body impact exposure also occurs on land in a variety of military and civilian offroad vehicles. The number of professionally used high-speed boats and their speed capabilities are increasing rapidly worldwide. We estimate that more than 2000 boats in the United States Navy, Army, Special Operations, and Coastguard can produce injurious slamming impacts.

While designing ships and boats, naval architects are expected to consider human factors and occupational health parameters onboard. Boat hulls and onboard equipment are typically designed to withstand 5 to 6-*g* peak impacts, and suspension seats are specified to mitigate impacts up to 4 to 5 *g* [7], although slamming-induced impacts to high-speed boats can exceed 20 *g* [13, 21]. Rules and regulations limit the allowable exposure to whole-body vibration [11], but exposure to a whole-body impact is very rarely measured. Regular operation of high-speed boats causes high vibration dose values, defined by the International Standardization Organization in the standard ISO 2631 [13, 17, 18]. British naval architects tested exposure onboard high-speed sea rescue boats (maximum 8.5 *g*) according to the ISO 2631 and found vibration dose values more than three times higher than the maximum daily dose of 21 ms$^{-1.75}$ permitted by the European Union in the EC Directive 2002/44 [2, 11]. This limit was exceeded after a few minutes of transit [2].

Despite this, few published studies we know of have estimated the incidence of injuries caused by slamming-induced impacts onboard high-speed boats. Ensign et al. [10] analyzed 121 self-reported injury events among 154 active-duty Special Forces high-speed boat operators (with a cumulative experience of 722 person-years) leading to 4218 days of limited job or mission performance. The authors concluded that the influence of shock and vibration on the development of these injuries could not be judged from the responses to this survey. A questionnaire study by Hurpin et al. [16] reported pain and medication use among 84 military high-speed boat operators (403 person-years) leading to 252 days of sick leave. The authors indicated that because musculoskeletal disorders were underreported in active operators, the reported incidence rates of injuries and use of pain medication in that survey were likely inaccurate.

The current study was therefore designed to investigate, among retired high-speed boat operators, (1) the self-reported incidence rate of impact-induced injuries, (2) the most common types of injuries or injury locations, (3) what impact characteristics were reported, and (4) the prevalence of self-reported sick leave, disability, and medical or orthopaedic treatment.

Materials and Methods

Study Design

This was a retrospective internet-based survey study among experienced military high-speed boat operators in the United

States regarding impact-induced injuries that were sustained onboard. The study is reported according to the Checklist for Reporting of Survey Studies [27] and contains the items of the Checklist for Reporting Results of Internet E-Surveys [12].

Development and Pretesting

The questionnaire was designed and made available in SurveyMonkey©. To guarantee full anonymity, we did not request that respondents register their identities or email address. The survey was developed by four senior experts in this field (one of whom is a former military high-speed boat operator), two orthopaedic surgeons, and one occupational medicine physician expert in the human factors of high-speed boats. The usability and technical functionality of the electronic questionnaire was tested before the internet survey was fielded.

Recruitment Process and Description of the Sample With Access to the Questionnaire

The target population for this study was that of the United States Navy Special Warfare Combatant Craft Crewmen (SWCC), who conduct maritime special operations in coastal and river environments using high-performance boats [29]. Approximately 800 SWCCs are on active duty, and there are 125 SWCCs in the reserve. The study was designed as a closed survey; the internet-based questionnaire was advertised through a link on the Combatant Craft Crewman Association online user group. The Combatant Craft Crewman Association has 360 members.

Survey Administration

To guarantee anonymity, the invitation was only published on the Combatant Craft Crewman Association user group's website and was not distributed by email. Participation in the survey was voluntary. No incentives were offered. The survey was open to responses for 11 days. It contained 31 items and was visualized on one screen (Table 1). Twenty-eight questions were multiple choice; the other three questions were open ended, and users were allowed to provide answers in a text box. The survey platform allowed respondents to review and change their answers before final submission.

Response Percentage

To maintain participants' anonymity, unique site visitors were not determined, because these numbers require the use of cookies or storage of internet protocol addresses. The participation percentage was determined by the unique number of people who agreed to participate by checking a checkbox, divided by visitors who visited the first page of the survey. A total of 59% (214 of 360) of those surveyed responded, and all who participated provided complete surveys.

Preventing Multiple Entries From the Same Individual

While designing the survey on the SurveyMonkey® platform, we chose not to allow the survey to be taken more than once from the same device. By default, the SurveyMonkey® platform prohibits a user from responding more than once from a single internet protocol address. This should have prevented multiple entries from the same individual.

Sample Characteristics

Eligibility

Inclusion criteria were previous service as a high-speed boat operator and previous employment as an SWCC. Exclusion criteria were age younger than 18 years and active SWCC status.

Sampling Techniques

This survey was distributed to a selected online user group as a closed survey without any randomization procedure.

Respondent Characteristics

In total, 214 individuals (213 men and one woman) with a mean age of 50 years (95% CI 41 to 59) and mean BMI of 29 kg/m^2 (95% CI 25 to 33) participated in the survey. A total of 97% (208 of 214) of the respondents were SWCCs. The median time served onboard was 9 years (range 1 to 28 years), and 93% of respondents have been deployed during their careers.

Variables, Outcome Measures, Data Sources, and Bias

We recorded age, gender, weight, height, and service branch (Navy, Army, Marine Corps, Coastguard, and Special Operations), service years and capacity (detachment chief, craft operator, craft navigator, crewman, engineer, or special forces operator), the number of injuries, service years onboard high-speed boat types

Table 1. Items of the questionnaire

1. Did you ever sustain any injury/injuries onboard a high-speed boat?
2. Can you recall at what age you sustained your first significant injury onboard a high-speed boat?
3. What year were you born?
4. What is your height?
5. What is your weight?
6. What is your gender?
7. In which branch did you serve onboard high-speed boats?
8. How long did you serve onboard high-speed boats?
9. In what capacity did you serve on high-speed boats?
10. Did you ever deploy on high-speed boats?
11. Please select your typical work during deployment. (More than one alternative possible.)
12. On which boat types did you serve and for how long?
13. On which boat type did you sustain an injury and to which part of the body? If yes, please specify how many injuries.
14. Did any of these injuries lead to sick leave or prevent you from participating in training or real-world missions?
15. What was the immediate cause of injury?
16. Can you describe the type(s) of injury - fracture, dislocation, disc rupture, strain, tear, fracture, dislocation, concussion, etc.? (open-ended question)
17. Did any impact sustained onboard affect or impair your capacity to do your job underway? If no, select 0. If yes, indicate the number of times.
18. How many injuries were examined by a medical professional? If none, select 0. If yes, indicate the number of examinations.
19. Have you ever had surgery for injuries sustained onboard while on active duty? If no, select 0; if yes, indicate the relevant number.
20. Did you have surgery after your military career for a condition related to your high-speed boat operations? If no, select 0. If yes, indicate the number of times.
21. Were you ever knocked unconscious while underway onboard a high-speed boat? If no, select 0. If yes, indicate the number of times unconscious.
22. Do you live with constant or recurring pain? If no, select 0. If yes, for how many years?
23. Do you live with reduced mobility, and if yes, for how long? If no, select 0. If yes, for how long?
24. Do you use any pain medication for a condition related to an impact-induced injury?
25. If you answered yes on the previous question, please state what pain medication you use. More than one box can be ticked.
26. Did you ever experience mental capacity impairments because of exposure to an impact?
27. How do you perceive your general health?
28. Did you ever choose to stand instead of sitting down to withstand an expected impact? If so, on what type of craft?
29. Have you applied for Veterans Administration disability? If no, skip. If yes, what is your rating?
30. Please indicate any relevant information and experiences. (open-ended question)
31. Please provide any feedback on this questionnaire. (open-ended question)

(MarkV, Long-range Combatant Craft Heavy, Combatant Craft Medium, Combatant Craft Assault, HSB High-Speed Boat, Navy Special Warfare 11-meter RIB, 10-meter RIB, and the 24-foot RIB) (Table 2), the age of participants at the time of the first injury, injury location, causes of injury (collision, capsizing, mainly vertical impact, mainly lateral impact, purely vertical impact, frontal head-on or "stuffing the boat," or seat bottoming out), symptoms of mild traumatic brain injury and impaired cognitive function, characteristics of the most injurious slamming impacts, duration of pain episodes (1 to 5 years, 6 to 10 years, > 10 years, or no pain), current frequency of pain medication (daily, weekly, monthly, or not using medication), type of pain treatment (acetaminophen, NSAIDs, opioids, injections, acupuncture, or other), perceived general health (five response options: poor, fair, good, very good, and excellent), surgical procedures while on active duty for injuries sustained on board (none, one, two, three, or four or more), surgical procedures after the military career related to injuries during service (none, one, two, and three or more), and Veteran's Affairs disability rating (0% to 100%) (Table 1).

Table 2. Specifications of high-speed boat types on which the study participants served

Type	Crew number	Maximum number of passengers	Length overall in feet	Maximum speed in knots
NSW 24 Foot RIB	3	4	24	> 25
NSW 10M RIB	3	8	30	> 35
NSW 11M RIB	3	10	33	> 40
Mark V Special Operations Craft	5	16	82	> 50
HSB High-Speed Boat	3	12	40	> 55
CCA Combatant Craft Assault	3	14	41	> 50
CCM Combatant Craft Medium	4	19	60	> 50
CCA Combatant Craft Heavy	7	12	80	> 50

Data Sources

The SurveyMonkey® platform provided a dataset with questionnaire results that were accessible using Microsoft Excel.

Biases

The main reason we chose to exclude active-duty SWCCs was to avoid bias caused by underreporting among service personnel, which has been identified as an issue [16]. Choosing retired SWCCs is associated with multiple other biases: The study's retrospective design results in recall bias in which memories of events change over time, affecting the collected data on impact directions and quality, as well as attribution of medical or surgical treatment to certain injurious events onboard. The study's design, which involved asking former operators whether their pain is caused by possible injuries as an SWCC, could be considered push polling by inducing a causality bias, and thus may inflate reported event frequencies. The selection bias caused by missing data from deceased SWCCs cannot be avoided in self-reported studies, but the worst injuries might remain unreported. Despite the above concerns, the results of this study add to what is known because this is the first survey we know of that engaged with retired SWCCs; surveying this group should have resulted in diminished employee underreporting bias. In addition, we had access to a unique sample of high-speed boat operators and had an adequate sample size to answer the questions of interest.

Ethical Approval

This study was approved by the Swedish Ethical Review Authority (number 2022-00603-01). The information provided to study participants included the length of the survey, which data were stored, where data were stored and for how long, who the investigator was, the purpose of the study, and that no personal information was collected or stored. The online survey was developed on an established survey platform that provided survey anonymity, as well as confidentiality and protection against unauthorized access.

Statistical Analysis

Because the aims of this study were exploratory, descriptive results are mainly presented. To estimate the incidence rate of self-reported impact-induced injuries, the number of self-reported injuries per person-year served onboard was calculated and is presented with a 95% confidence interval. Data on boat type, types of events, injury location, severity, pain, disability, and need for treatment are presented as proportions with numerator and denominator in parentheses. To consider the possible effect of nonresponders, we performed a best-case analysis that assumed nonresponders had the same mean years of service as responders, but that none of them have experienced injuries or chronic pain. The required sample size for a 95% CI and a 5% margin of error was 187, based on a Cochran sample size formula (assuming the Combatant Craft Crewman Association population was 360 members [8]).

Results

Incidence Rate of Injuries and Percentage of Servicemembers Reporting an Injury

The incidence rate reported by the participants was 1.1 injuries per person-year served. The 214 operators reported a total of 2460 impact-related injuries over 2318 person-years served onboard. Ninety-one percent (195 of 214) reported one or more injuries sustained onboard a high-speed boat.

Most Common Injury Types and Injury Locations

The most common injury locations were the back (31% [775 of 2460]), neck (21% [509 of 2460]), head (16% [392 of 2460]), leg or foot (12% [284 of 2460]), torso (11% [269 of 2460]), and arm or hand (9% [231 of 2460]) (Fig. 1). Thirty-three percent (70 of 214) reported experiencing one or more (range 1 to 15) impact-induced events of loss of consciousness, and 70% (149 of 214) reported having experienced impaired capability to perform their job onboard because of impact exposure. Overall, responding high-speed boat operators experienced a mean of four back injuries, three neck injuries, two head injuries, one torso injury, one upper extremity injury, and one lower extremity injury during a 10-year period of service.

Impact Characteristics

A total of 1827 injuries were reported, along with their characteristics. Of these, 49% (889 of 1827) of injuries were perceived by the respondents to be caused by an impact containing some or mainly lateral forces, and 12% (218 of 1827) were perceived to be caused by purely vertical impacts (Fig. 2). Eighteen percent (333 of 1827) blamed their injury on frontal impacts (stuffing impacts), 14% (262 of 1827) blamed them on seats bottoming out, 6% (101 of 1827) on collisions, and 0.5% (six of 1827) on capsizing.

Surgical Treatment and Residual Disability

Thirty-nine percent (84 of 214) of respondents reported undergoing surgery to treat an injury related to an impact while serving onboard during active duty (Fig. 3), and 34% (72 of 214) reported having had surgery after retirement to treat an injury related to an impact while serving onboard.

While on active duty, 14% (31 of 214) of respondents underwent one surgical procedure, 8% (18 of 214) had two, 7% (15 of 214) had three, and 9% (19 of 214) had four or more surgical procedures (Fig. 3). After their military career, 15% (33 of 214) of participants had one procedure, 10% (21 of 214) had two, and 8% (18 of 214) had three or more procedures.

The participants' self-perceived general health was excellent in 2% (five of 214), very good in 15% (33 of 214), good in 40% (85 of 214), fair in 31% (66 of 214), and poor in 12% (25 of 214).

Only 8% (17 of 214) of participants did not report any pain. Eight percent (17 of 214) reported constant or recurring pain for 1 to 5 years, 27% (58 of 214) reported having pain for 6 to 10 years, and 57% (122 of 214) reported having pain for 11 years or longer (Fig. 4).

Among all participants 72% (155 of 214) applied for a Veterans Affairs disability rating. Sixty-eight percent (105 of 155) of these had a Veterans Affairs disability rating of 50% or more, and 11% (17 of 155) had no disability according to their Veterans Affairs rating.

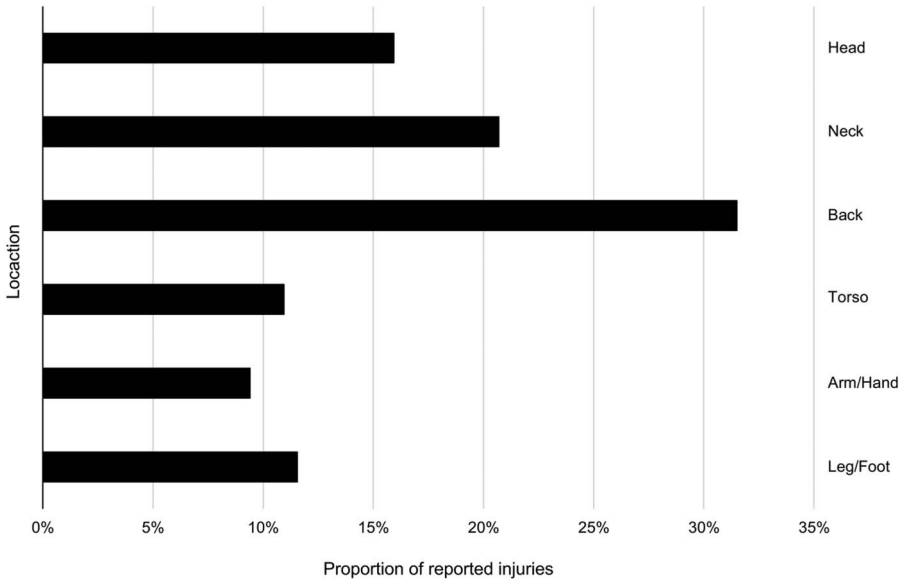

Fig. 1 This bar chart represents the distribution of high-speed boat impact-related injuries of six body regions, as reported by the participants.

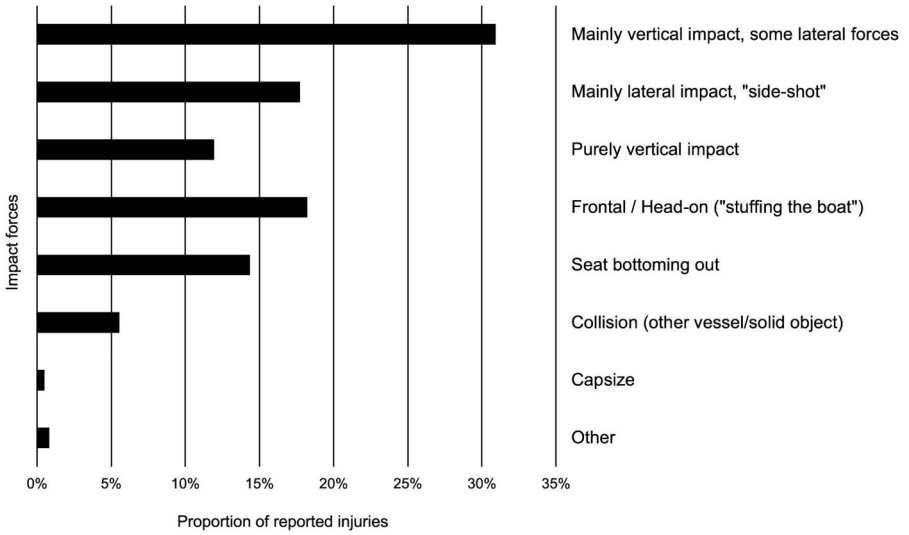

Fig. 2 This bar chart represents the distribution of the types of injurious impacts onboard high-speed boats, as reported by the participants.

Currently, 42% (89 of 214) of the participants use daily pain medication, 19% (41 of 214) use it weekly, and 14% (30 of 214) use it monthly. The participants use NSAIDs the most often (62% [133 of 214]), followed by acetaminophen (29% [63 of 214]) and opioids (17% [36 of 214]). Twenty percent (43 of 214) currently use other types of medication, including gabapentin, corticosteroids, and alcohol as painkillers. Nineteen percent of respondents receive local injections (40 of 214), and 30% (64 of 214) receive acupuncture.

Secondary Analyses: Best-case Scenario

To present the effect of nonresponders among the eligible population, we performed the above calculations with a best-case scenario including all 360 members of the eligible population. The impact-related injury incidence rate was 0.6 injuries per person-year served (2460 injuries for 3899 person-years) in this scenario.

In the best case, 19% (70 of 360) of respondents reported experiencing at least one impact-induced event of loss of

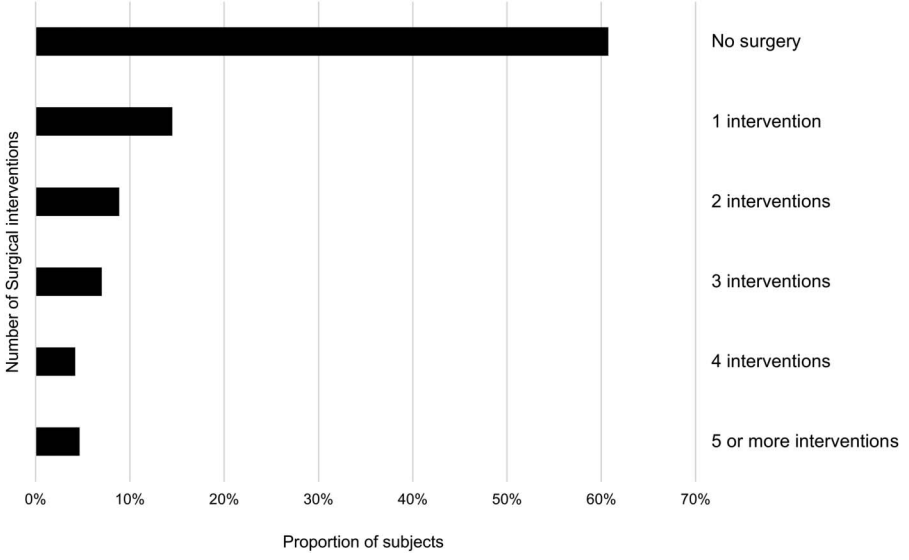

Fig. 3 This bar chart represents the proportion of participants given surgical interventions for injuries sustained onboard high-speed boats during active duty.

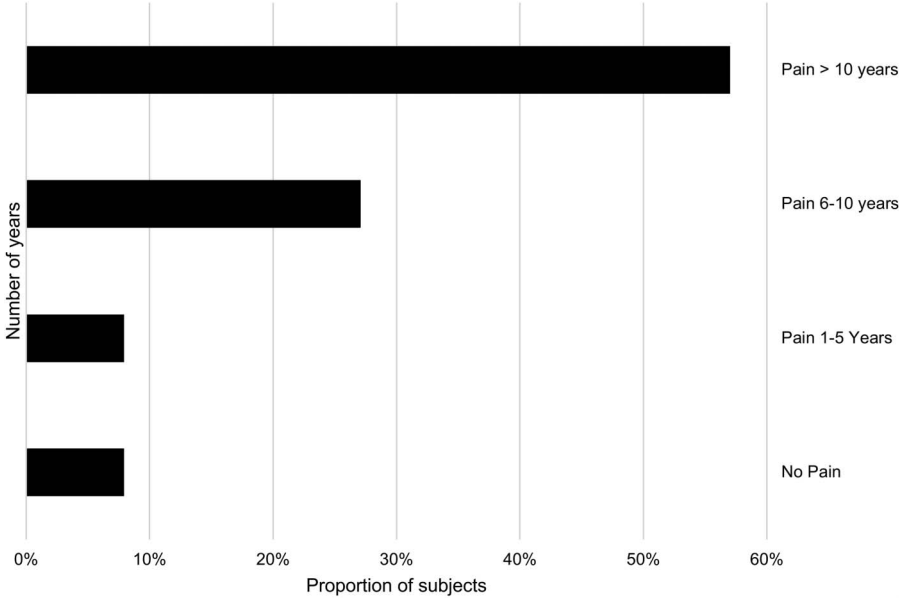

Fig. 4 This bar chart represents the self-reported number of years with constant or recurring pain among retired high-speed boat operators.

consciousness, and 29% (105 of 360) reported having experienced impact-induced events of impaired performance onboard because of an impact. In the best-case scenario, 24% (87 of 360) reported having surgery while on active duty—and 21% (77 of 360) after retirement—to treat an injury related to an impact while serving onboard.

In the best-case scenario, 45% (163 of 360) of participants did not report any pain. Five percent (17 of 360) reported constant or recurring pain for 1 to 5 years, 16% (58 of 360) reported having pain for 6 to 10 years, and 34% (122 of 360) reported having pain for 11 years or longer. In the best case, 25% (90 of 360) of the participants currently use daily pain medication, 11% (41 of 360) use it weekly, and 8% (30 of 360) use it monthly.

Discussion

High-speed boats are widely used by military, law enforcement, and even civilian businesses. Although it is well known that people sustain injuries while working on these boats, to our knowledge, only two studies have evaluated those injuries, both of which have severe limitations [10, 16]. We therefore surveyed retired special-warfare servicemembers whose careers were spent on those boats. We found that nine of 10 of such servicemembers sustained an injury on one of those boats, and that a high proportion of those injuries were severe, resulting in surgery, time off work, and even chronic pain resulting in frequent analgesic used. Based on our findings, we believe high-speed boat operators face severe occupational health threats that could be prevented by the choice of high-speed boat type and/or constraining speeds to reduce harmful exposure, while the effects of impact exposure could be mitigated through physical training programs.

Limitations

One limitation is related to nonresponse bias, because it is unknown how many of the 360 members of the Combatant Craft Crewman Association received the invitation to participate. With responses from 214 of the possible 360 respondents, it is theoretically possible that up to 40% did not respond. To visualize the effect of nonresponders, a best-case scenario was created in which all 360 eligible individuals were included, and nonresponders were handled as if they did not have any history of injuries or chronic pain. More than 50% reported pain in the best-case scenario, and more than 40% use regular pain medication; these numbers are higher than those in the general population. According to the Centers for Disease Control, among patients aged 45 to 64 years, 28% of people reported chronic pain (pain on most days or every day in the past 6 months), and 12% had chronic pain because of high impacts (chronic pain limiting life or work activities on most days or every day in the past 6 months) [9]. The distribution of the kinds of injuries and impacts causing them would still represent perceived injuries. Another potential bias is related to multiple entries from the same individual. To prevent this in this survey, SurveyMonkey®

does not accept multiple entries from the same internet protocol address. However, manipulation cannot be ruled out in an anonymous online survey.

Additionally, there is transfer (or attrition) bias in all self-reported studies of this type; any fatal injuries are not recognized. The true number of injuries could be higher than the number reported in the current study. Further contributing to the potential for underreporting is the observation that active-duty personnel in jobs as military pilots and high-speed boat operators might underreport injuries and symptoms because injuries could disqualify them for service [15]. Therefore, many operators seek medical care outside the military medical system, and military healthcare records may be insufficient to statistically corroborate our findings. This study excluded high-speed boat operators still in active service to mitigate this bias.

A survey such as ours raises a concern about push-polling, although for reasons discussed earlier, we do not see this as very likely. In addition, there is the potential for participants to infer causality and overestimate injuries in response to surveys such as this, because more-injured and more-severely injured participants likely are more inclined to respond. Because the reported impact-related injuries match the reported pain medication and Veterans Affairs disability rating, the self-reported causality is valuable because it provides information on health perceptions among high-speed boat operators.

Because the cohort consisted of Special Forces operators, they may have been exposed to injuries unrelated to high-speed boat operations, both before and during service as an SWCC. We asked specifically about injuries related to impact exposure, but regarding chronic pain and surgical treatments used, the presented results must be interpreted cautiously.

Finally, because the survey was retrospective, a recall bias should be assumed, in which memories of injuries may be lost or strengthened. We believe this bias would affect the quality and frequency of injuries more than the number of individuals who experienced harmful impacts. Because of this, conclusions about quality and frequency need to be made cautiously. Current data that can be validated, such as age, gender, military branch, and Veteran's Affairs disability rating, are less likely to be affected by recall bias.

Injury Rate

The reported overall injury rate was substantially higher than previously believed and reported by personnel still on active duty [10]. The operators in our study reported more than one injury per year served onboard. According to the United States Bureau of Labor Statistics, 2.2 injuries per 100 full-time working employees were recorded in 2020. Thus, high-speed boat operators report a 50-times higher injury incidence rate than the civilian employee population. These self-reported injury rates warrant preventive occupational health measures that must also be applicable to civilians who operate high-speed boats.

Impact and Cognitive Symptoms

Cognitive impairment or sick leave after impact-induced injury was reported by most responders to this survey. The high numbers of reported events of reduced cognitive capability and unconsciousness are troublesome for two reasons. First, repeated events may cause mild traumatic brain injury. Mild traumatic brain injury has been defined as a mild insult to the head that results in a brief period of unconsciousness, followed by impaired cognitive function [20]. In our study, 34% (72 of 214) of operators reported a total of 148 events of loss of consciousness. The long-term effects of mild traumatic brain injury may lead to disability and chronically impaired cognitive function [25]. Neuropathologic studies on the brains of deceased Special Forces operators found signs of chronic traumatic encephalopathy in 17% (four of 24) [22, 23]. Second, 49% (105 of 214) of the operators in our study reported a history of cognitive impairment onboard because of impact exposure. Although cognitive impairment was not measured objectively, reduced cognitive capability and indeed unconsciousness may impair safety onboard in challenging environments, as well as operational capabilities and combat readiness.

Impact Characteristics

The survey results suggest that lateral impact vectors are perceived to be involved in about half of injurious events. Only 12% (218 of 1827) of impact respondents claimed caused injuries were perceived to be purely vertical; 18% (333 of 1827) were perceived to be frontal, head-on impacts; and 49% (889 of 1827) were perceived to contain lateral forces. Because recall bias must be assumed, no conclusions can be drawn from this study except that former high-speed boat operators report lateral forces played a role in their injuries. The importance of horizontal, especially lateral, forces during impacts at sea is unknown. In motor vehicle collisions, lateral impact forces cause more severe and lethal injuries [14]. However, in high-speed boats, the effects of oblique and lateral whole-body impact exposure have not been studied.

It is still unknown what kinds and levels of impacts are safe and at what level they become dangerous. The general perception among boatbuilders and in many agencies is that hull impacts do not exceed 10 g (98.2 m/s^2), and that only purely vertical impact-induced forces cause injuries [21]. In reality, slamming-induced hull impact peak values can exceed 25 g (245 m/s^2), which is more than fighter pilots sustain from seat ejections. Acute injuries are rarely caused by vibration alone,

but rather by impacts. Still, impact peak values do not fully correlate to the risk of injury. Equally important is the pace of acceleration. This onset factor is called jerk and defines the peak acceleration value, divided by the time it takes to reach it (Δ a/Δ t), in m/s^3. For example, a trained fighter pilot in a sharp turn can pull 7 to 9 *g* without sustaining injuries, because the onset of *g*-load (acceleration) is as slow as 1 second (1000 ms), while a hydroplaning boat slamming onto the water's surface can easily reach more than 10 *g* in less than 10 ms, producing a 100-times higher jerk. The significance of the jerk regarding the severity of impact-induced injuries is still unknown. There is a need for further research analyzing the actual impact levels and characteristics of impact-induced forces acting on humans onboard high-speed boats and to establish what kinds and magnitudes of exposure are sustainable.

Surgical Treatment and Residual Disability

Many of those who served on these boats reported undergoing surgery for an injury experienced during service, and more than half reported receiving ongoing disability benefits from the Veterans Affairs system. Many operators reported having had surgery while on active duty for an injury sustained on board, and one-third reported surgery after retirement. Forty-one percent (87 of 214) of operators in our study reported a Veterans Affairs disability rating of 70% to 100%. This results in substantial compensation costs for the Department of Defense, considering how early many operators retire, especially if such numbers would represent the whole group.

Practical Implementation of the Study Results

It is necessary to prevent impact-induced injuries and mitigate the need for impact-related operational restrictions. The obviously positive dose-response ratio observed, in which greater exposures cause more severe problems, makes it imperative to control exposures. Various means to reduce impact exposure are being discussed, and have been implemented to various degrees in different countries. The most obvious and effective is to adapt a boat's speed to the prevailing sea conditions. However, most professional high-speed boats sometimes must be driven at the highest appropriate speed.

Some agencies provide physical training programs to exposed personnel aiming to strengthen the musculoskeletal system. Such programs would preferably even include proprioceptive neuromuscular facilitation training to prepare for multidirectional impact exposure [4, 24]. Furthermore, educational programs on the biomechanics of exposure onboard high-speed boats could increase awareness of the importance of body posture to impacts.

Other recommended means to reduce exposure and maintain physical readiness include training and vetting boat operators based on driving skills, adapting training and operational routines to prevailing sea conditions, educating commanding officers on the benefits of teams fit for mission reaching their targets, and educating acquisition officials on the need to specify boats with hull shapes offering acceptable ride quality and suspension seats scientifically proven to mitigate injurious impacts. Some of these means, in particular choosing a safe maximum boat velocity, require knowledge not yet available, namely, what kinds and what magnitudes of impact are safe versus what exposures are dangerous. To establish this, a prospective multinational study is planned under the NATO Science and Technology Organization, Human Factors and Medicine Panel (HFM-344), including military and civilian high-speed boat operators (ClinicalTrials.gov Identifier: NCT05299736).

Conclusion

Exposure to slamming-induced impacts on high-speed boats seems to cause injuries, reduced performance, and decreased combat readiness. Orthopaedic surgeons might treat retired or active-duty military or civilian high-speed boat operators in clinic. To maintain the operator's health and ability to work, the occupational hazard of slamming impact exposure must be prevented or mitigated. There are several ways to prevent these injuries and maintain physical readiness, perhaps starting with adapting the boat speed to sea conditions. Other approaches include training and vetting boat operators based on their driving skills, adapting training and operational routines, educating commanding officers on the benefits of teams fit for mission reaching their targets, and educating acquisition officials on the need to specify boats with hull shapes offering acceptable ride quality and suspension seats scientifically proven to mitigate injurious impacts. After an injury, rehabilitation of high-speed boat operators could include core-strengthening physical training and proprioceptive neuromuscular facilitation.

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