whalestrike: An R package for simulating ship strikes on whales

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Summary

The collision of ships with whales can result in serious injury or death of the animal. This is particularly concerning for endangered species such as the North Atlantic right whale. Although speed reduction policies have been developed and implemented, simple considerations suggest that other factors, such as ship mass and prow shape, should also be taken into account. An R package called `whalestrike` has been developed to address such issues. It was used by Kelley, Vlasic, and Brillant (2021) in the development of a biomechanically based criterion for the lethality of ship strikes, but this was just a starting point. The next step, and goal of the present paper, is to introduce the model code to a broader community, encouraging its use and development by diverse researchers and policy makers.

Statement of need

Ship collisions pose significant threats to endangered marine mammals (Laist et al. 2001). The case of the North Atlantic right whale (*Eubalaena glacialis*) is of particular concern, since it is considered a "Critically Endangered" species (IUCN 2020). The trend is not encouraging for this animal, the population of which was 340 ± 7 in 2021 (Pettis, Pace, and Hamilton 2023), down significantly from 483 in 2010 (Pace, Corkeron, and Kraus 2017). According to necropsy studies, ship strikes are involved in over half of right whale deaths (Campbell-Malone et al. 2008).

Motivated by such studies, efforts have been made in recent years to mitigate the consequences of collision by imposing speed restrictions on ships, and evidence of successful results (e.g. Conn and Silber 2013) has led to marine policy changes, including both static and dynamic zones of speed restriction (e.g. Transport Canada 2023). Even so, it seems unwise to measure the success of speed restrictions by counting dead or injured whales, given the low numbers alive today. In addition, basic reasoning reveals that speed cannot be the only factor. Variations in ship mass, prow shape, etc. should also be considered, along with whale morphometric parameters, making for a multifactorial problem that requires even more data to achieve statistical reliability.

With this in mind, Kelley, Vlasic, and Brillant (2021) devised a simple numerical model of the biophysical dynamics of collisions between vessels and whales. This involved using published records of whale injury and death (across multiple species) to calibrate a lethality criterion that depends not just on vessel speed, but also on other factors such as vessel mass, prow geometry, etc., in addition to whale morphometric parameters. The model was expressed in the R language, because it is familiar to many marine biologists and because it provides a wide scope of statistical tools for followup work. The purpose of the present paper is not to recapitulate the results of Kelley, Vlasic, and Brillant (2021), but rather to introduce readers to the `whalestrike` code.

To the author's knowledge, there are no other R packages that address the topic of collision mechanics and whale lethality in this way. Readers interested in the related topic of the probability of collision given shipping patterns and whale distributions might find it helpful to start with R packages named `whalemap` (Johnson, Morrison, and Taggart (2021)) and `shipstrike` (Keen (2023)).

Model formulation

A desire to produce a GUI (graphical user interface) tool permitting easy exploration of various model scenarios led to a decision to create a simplified model that yields results quickly, as opposed to a much more computationally-expensive finite element model that might account more accurately for the deformation of whale flesh (see e.g. Raymond 2007). The new model ignores ship deformation upon impact, and considers whale deformation to occur only in a specified impact area dictated by the geometry of the ship's prow. It uses a layered scheme to represent the whale, with skin covering blubber, with that blubber covering a sub-layer representing a combination of muscle and organs, and with bone at the core. Thicknesses and material properties (including a nonlinear stress-strain relationship) for each layer are taken from the literature, with the idea being that adjusting these parameters will provide a way to simulate strikes on different species, or at different body locations. Skin deformation is modeled with both extension and compression forces, while only compression is considered for interior layers. Lacking reliable information on failure limits for these biomaterials, critical values for stresses are posited in the context of published results of the damage experienced in documented ship strikes. Kelley, Vlasic, and Brillant (2021) provide more information on the methodologies and issues involved.

The model is simple, with acceleration and forces being linked via Newton's second law. Numerical integration is carried out with the `lsoda()` function of the `deSolve` R package (Soetaert, Petzoldt, and Setzer 2010). Predicted velocities are used in computing water drag and the relative positions of ship and whale. After contact is made, extensive and compressive forces arise, and the stresses associated with these forces are monitored in the context of the lethality index proposed by Kelley, Vlasic, and Brillant (2021). Dynamical elements involved in this process are distilled into several dozen model parameters. Although a great deal of effort has been put into formulating these parameters appropriately (mainly for application to right whales), `whalestrike` offers a simple way for users to adjust each of them, if needed for new applications.

Package installation and use

The package may be installed from its development website by typing

```
library(remotes)
install_github("dankelley/whalestrike", ref="main")
```

in an R console[1]. Once this is done, the user has access to over 20 functions and their documentation. The latter makes frequent reference to the scientific literature, since the package is aimed at scientists and managers who seek to trace the sources of the formulae involved in a computation. A vignette is also provided for wider context.

A good way to start using `whalestrike` is to become familiar with `strike()`, a function that simulates a collision event and produces an object that can then be plotted (using the R generic function system) in multiple ways.

Three arguments must be provided to `strike()`. The first sets the times at which model output is desired, the second establishes the initial locations and speeds of the ship and the whale, and the third describes the biological and physical properties of the ship and the whale. An example is provided in the documentation of `strike()`, e.g. typing

```
library(whalestrike)
example(strike)
```

in an R console will run a sample simulation, and show a three-panel plot (reproduced here as Figure 1) of the relative position of whale and ship, the compression of the whale's layers, and the associated lethality index.

[1] There are plans to submit `whalestrike` to the Comprehensive R Archive Network (CRAN 2024).

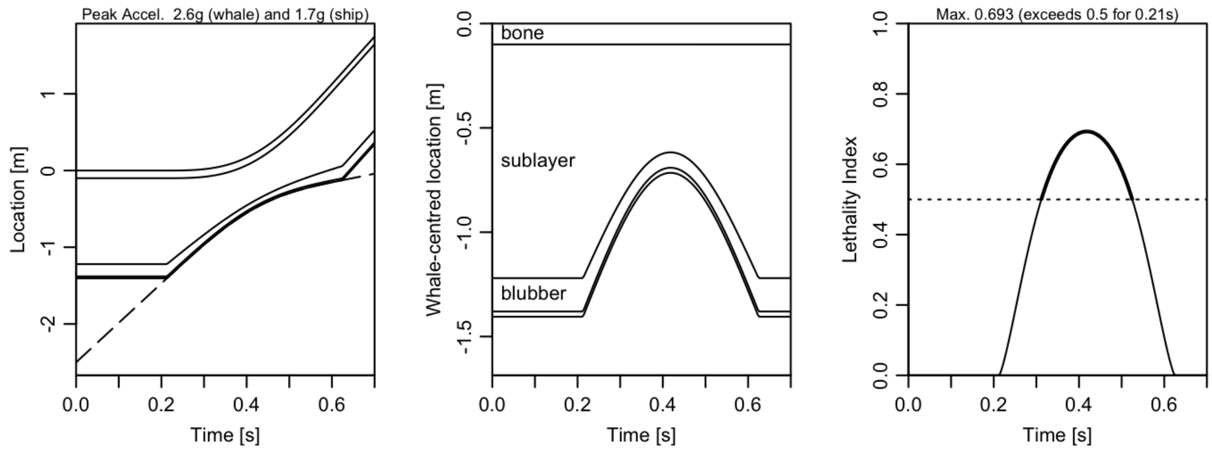

Figure 1: Diagram produced by typing `example(strike,package="whalestrike")` in an R session. Three of the possible 12 plots are shown. **Left:** positions of 45-tonne vessel initially moving at 10 knots (dashed line) and the boundaries between the three layers on the shipward side of the whale. Contact occurs at about 0.2 s, and continues to about 0.6 s. Note that a small fishing vessel is used in this simulation, and so its speed is significantly reduced by the collision. **Middle:** As the left panel, but showing only the positions of the interfaces between the whale layers, relative to the whale's centre position. In this view, the thin skin can be seen at the bottom, with blubber, sublayer and then bone to the interior. **Right:** An index of lethality, with the line thickened for the interval during which stresses are predicted to exceed a threshold for lethal damage according to Kelley, Vlasic, and Brillant (2021).

Running the simulation and plotting the results as in Figure 1 takes a fraction of a second on a typical laptop, showing that the system is computationally inexpensive. This is helpful in detailed studies that involve calling `strike()` with a wide suite of parameter values, such as the creation of the diagrams in Kelley, Vlasic, and Brillant (2021), some of which involved of order 10^5 model runs to cover parameter space in detail.

There are also applications for which a few model runs may suffice. For such work, `whalestrike` provides an R-shiny application that is run by executing the following in an R console.

```r
library(whalestrike)
app2()
```

Doing this creates a window, shown in Figure 2 here and in video form online (Kelley 2024). With a variety of sliders and other GUI elements, the application makes it easy to explore "what if" scenarios for ship strikes. For example, monitoring the Lethality Index plot while adjusting the ship-specification tools and the impact speed might prove useful in discussions of speed restrictions across ship masses and classes. More detailed (and reproducible) work is also facilitated by `app2()`, because it can display the underlying code used in the simulation, providing a good starting point for more extensive analyses, such as the exploration of covarying parameters.

Conclusions

The `whalestrike` package is intended to provide guidance for the development of marine policies related to ship speeds. It is written in R, a language that is familiar to many marine biologists, and one that also offers a vast array of statistical tools for analysing the results of model simulations. In addition to tools for detailed control of simulations, the package also provides a GUI-based tools for basic exploration, which may be useful in making or explaining policy decisions.

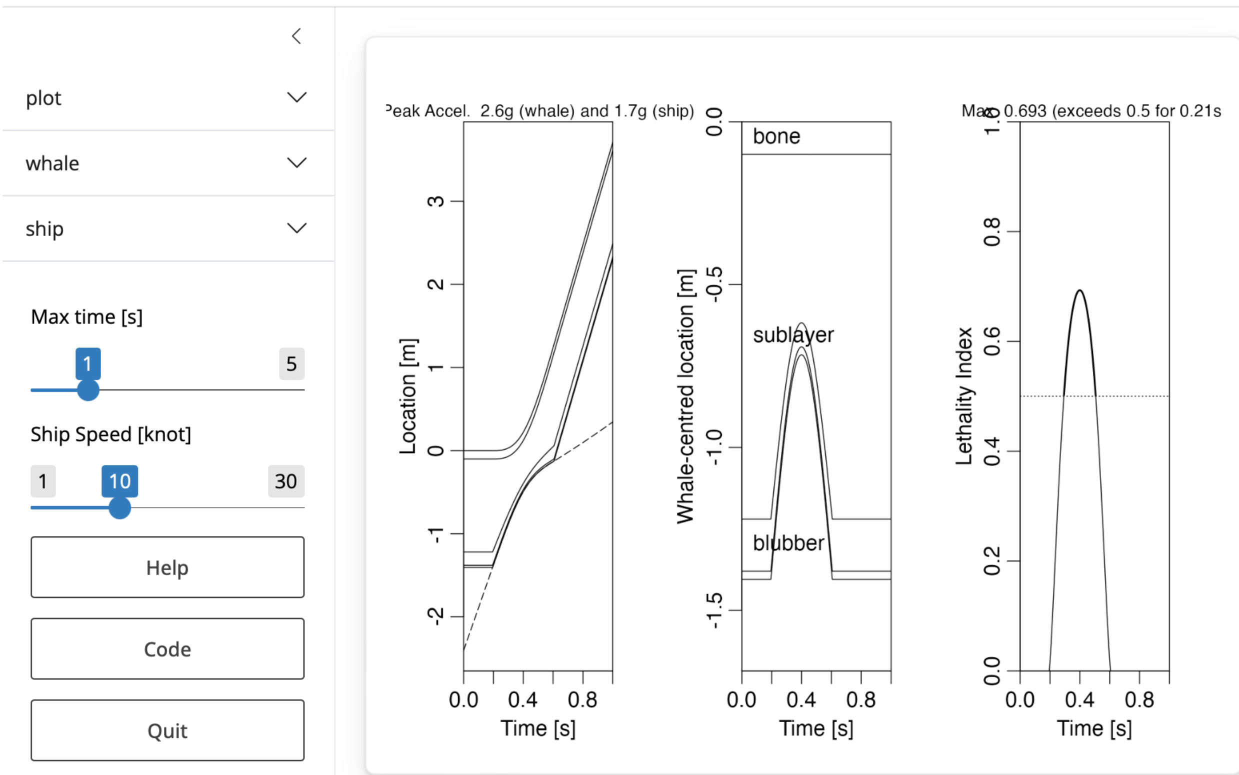

Figure 2: View of an interactive application for simulating ship-whale collisions. Adjusting the slider for ship speed will reveal that the vessel in this simulation would have to slow down to 6.5 knots in order to reduce the inferred Lethality Index below a critical value (dashed line in right panel).

Being founded on physical principles, `whalestrike` complements the more statistical approaches of most studies in this field. An advantage of this foundation is a reduction in the need for a database of collision events that covers the relevant range of ship types and speeds. This is especially important for an application such as this, because each entry in a collision database represents the loss of one more member of a species that is already at high risk of extinction.

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