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Empirical determination of severe trauma in seals from collisions with tidal turbine blades

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Abstract

1. Tidal energy converters (turbines) are being developed in many countries as part of attempts to reduce reliance on hydrocarbon fuels. However, the moving blades of tidal turbines pose potential collision risks for marine animals. Accurate assessment of mortality risk as a result of collisions is essential for risk management during planning and consenting processes for marine energy developments. In the absence of information on the physical consequences of such collisions, predicting likely risks relies on theoretical collision risk models. The application of these at a population level usually assumes that all collisions result in mortality. This is unlikely and the approach therefore produces upwardly biased estimates of population consequences.
2. In this study, we estimate the pathological consequences of direct collisions with tidal turbines using seal carcasses and physical models of tidal turbine blades. We quantify severe trauma at a range of impact speeds and to different areas of seal carcasses. A dose-response model was developed with associated uncertainty to determine an impact speed threshold of severe trauma to use in future collision risk models.
3. Results showed that severe trauma was restricted to the thoracic region, with no evidence of injury to the lumbar or cervical spine. Pathological indicators of mortality were only predicted to occur in collision speeds in excess of 5.1 $m.s^{-1}$ (95% c.i. 3.2 to 6.6) and was affected by body condition; increasing blubber depth reduced the likelihood of severe trauma.
4. *Synthesis and applications*. This study provides important information for policy makers and regulators looking to predict the potential impacts of tidal turbines on marine mammals. We demonstrate that the probability of severe trauma in seals due to collisions with turbine blades is highly dependent upon collision speed, and that the majority of predicted collisions are unlikely to cause fatal skeletal trauma. We recommend that collision risk models

incorporate appropriate mortality assumptions to ensure accurate estimates of the population consequences are produced in risk assessments for tidal turbine deployments.

1. Introduction

Over the past few decades, marine environments have experienced rapid industrialisation, with increases in marine transportation, oil and gas exploration and extraction, aquaculture and fisheries (Smith 2000). Many of these activities can lead to negative impacts such as vessel collisions (Vanderlaan & Taggart 2007) and fisheries gear entanglement and bycatch (Read, Drinker & Northridge 2006) which pose acute traumatic risks to marine mammals. In many cases, the nature and extent of human interactions can have important consequences for the demographics of affected populations and pose an existential threat to some species (Read, Drinker & Northridge 2006). More recently, a number of novel technologies in the marine energy sector have emerged that have the potential to kill or injure marine species. For example, tidal stream energy extraction is being developed in several countries; this is typically carried out using large floating or seabed-mounted turbines that extract kinetic energy from tidally-driven, moving water (Boehlert & Gill 2010; Sparling, Lonergan & McConnell 2017). Proposed energy developments comprise large arrays of such turbines deployed in tidally energetic coastal environments (Boehlert & Gill 2010). Evidence also suggests that marine predators are attracted to tidally energetic regions (Alldredge & Hamner 1980; Wolanski & Hamner 1988). Further, static structures may increase primary productivity through artificial reefs which are known to attract top-predators (Todd *et al.* 2009; Russell *et al.* 2014). The likely spatial overlap between tidal turbines and marine mammals has led to concerns about potential impacts on these species. Rotor speeds are often relatively high, with tip speeds of up to 12 $m.s^{-1}$ (43$km.h^{-1}$)(Sparling, Lonergan & McConnell 2017), three times the collision speeds thought to kill large cetaceans during ship strikes (Vanderlaan & Taggart 2007). Although there is evidence to suggest that seals exhibit avoidance responses to the acoustic cues of tidal turbines

(Hastie *et al.* 2017), estimated avoidance rates were relatively low and there remains a potential that collisions with rotating turbine blades may cause direct mortality.

The risk of collisions with marine mammals depends on the numbers of animals at the tidal sites, their natural behaviour and any behavioural responses to encountering turbines. At present there are no empirical data on collision rates between marine mammals and operating turbines, and no information on the physical consequences of such collisions. Predicting the impacts of tidal turbines on marine mammals therefore relies on theoretical collision-risk models. These combine available information or assumptions about animal behaviour and the spatial and temporal patterns of animal abundance to estimate numbers of potential collisions between animals and turbines. Estimates can then be used to predict population consequences of proposed turbine deployments (e.g. Band, 2000; Wilson *et al.* 2006; Band, 2016). To date, estimates of population level effects have been based on a precautionary assumption that all collisions result in death or permanent disablement of the animals involved (Wilson *et al.* 2006; Band *et al.* 2016). This assumption is unlikely to be true for all cases, and the models may therefore produce inaccurate predictions about the effects on populations of marine mammals. Further, although it may be reasonable to assume that high speed collisions will cause injury, turbine blade tip-speeds vary over a tidal cycle and are zero at low flow rates around slack tide. The speed of impact also varies along the turbine blade, increasing linearly along the length of the blade from zero at the root to a maximum speed at the blade tip.

To date, only two studies have explored the validity of the mortality assumption. Carlson *et al*. (2014) and Copping *et al.* (2017) used a range of skin and blubber morphometrics of killer whales (*Orcinus orca*) and harbour seals (*Phoca vitulina*) respectively to investigate the potential energy transfer from blade to individual. Although the authors present a range of severities and provide useful insight into how collisions can vary over a tidal cycle, the collisions were simulated and damage to the skeletal system and internal organs, and hence probability of mortality, was not directly measured.

In this study, we investigate the physical consequences of collisions between seal carcasses and a replica tidal turbine blade. We carried out a series of experimental trials to quantify the physical damage and assess the relationship between collision speed and the probability of inducing severe, traumatic injuries.

2. Materials and Methods

2.1 Experimental set-up

To determine the consequences of collisions between seals and tidal turbines a full-scale replica of the leading edge of a turbine blade tip section was constructed and fixed to the bow of a jet-drive boat to carry out a series of controlled collisions with seal carcasses (Fig. 1).

The 840mm long, straight edged replica was made from reinforced PVC blocks (Supplementary material) and had the same profile as the leading edge of the tip of an Andritz Hydro Hammerfest HS1000 (http://www.andritzhydrohammerfest.co.uk) turbine blade. The tip represents the part of the blade with the narrowest leading edge and therefore the most damaging point of contact. We took this approach to ensure that collisions represented the worst-case scenario and therefore produce conservative estimates of damage. The base of the blade was angled backwards ~5^{o} from vertical to achieve a slight downward component of the impact to ensure that carcasses remained submerged throughout the collision while maintaining an angle of attack close to perpendicular to the motion of the blade. Perpendicular strike orientation was required to ensure maximum energy transfer to the strike location (Grear *et al.* 2018).

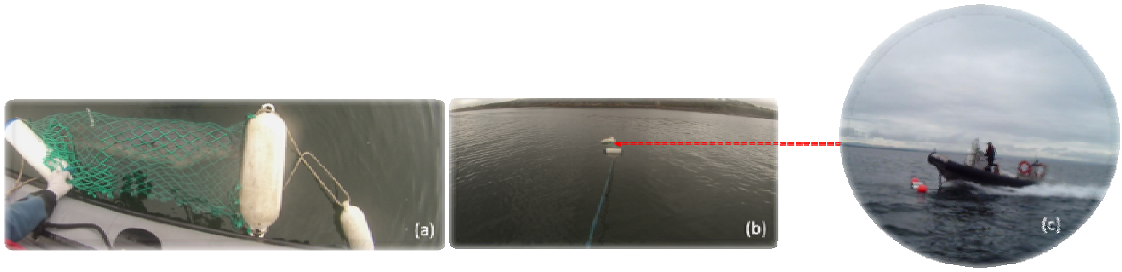

Figure 1: Trial set-up. (a) the seal carcass oriented in a coarse mesh, net bag attached at each end to flotation buoys. Note the dorsal surface of the seal carcass presented in the top of the photograph and the head-to-tail orientation following the length of the bag. (b) the seal carcass suspended on the surface of the water with a quick release line attached to one flotation buoy. (c) the vessel with the simulated turbine blade immediately prior to an impact. Note the vertical orientation of the model turbine blade on the keel of the boat and the perpendicular orientation of the boat with respect to the seal carcass.

Seal carcasses were collected for collision trials between 2014 and 2017. A total of nineteen carcasses, 12 males and 7 females, were collected; one juvenile and two adult grey seals (*Halichoerus grypus*) were collected as stranded carcasses, fifteen were juvenile grey seals by-caught in fishing nets in the south-west of England and one adult male harbour seal from the west coast of Scotland.

All carcasses were visually assessed at collection for obvious signs of pre-existing trauma, decomposition, or emaciation. Skeletal trauma was broadly assessed on site through palpation and tactile investigation before being collected and returned to laboratory conditions where further assessment could take place. Suitable carcasses were frozen at -20°C. No experimental bias was imposed on the carcass collection in that all carcasses which met the criteria of decomposition state were considered, regardless of age, sex or species.

Prior to the collision trial, each carcass was subjected to computed tomography (CT) scans to assess any pre-existing trauma. This provided a baseline from which we could assess damage resulting from the collision trials. Morphometric data of length, girth and mass was also taken. All individuals which were used in the final trials were judged to be in good physical health and showed no signs of emaciation.

Collision trials took place during calm (Beaufort 0-2) weather in a sheltered bay on the east coast of Scotland. Carcasses were defrosted at ambient temperature for 10 days prior to collision trials in September 2016 and 2017 to ensure complete thawing of the soft tissue. In each trial the jet boat was driven at the carcass at a pre-determined speed. The boat was positioned accurately enough to successfully collide with a pre-determined target area on the carcass (Fig, 1; Supplementary material). Collision locations were confirmed with a downward facing, bow-mounted, high definition (720p) video recorder (Vivitar ™ Action Cam DVR782HD), recording at a frame rate of 30 fps. Collision trials were designed to cover a range of impact speeds which represented the expected tip speeds of operational tidal turbines (Sparling, Lonergan & McConnell 2017). During a trial, each carcass was subjected to multiple collisions. However, each collision location on that carcass was targeted only once as multiple strikes to the same location could compound effects by progressively weakening the skeleton; this assumes that collisions to discrete locations did not weaken other parts of the skeleton. Dorsal collisions were expected to give the highest likelihood of skeletal trauma given the exposure of the spine and its connection to the skull, rib-cage and pelvis. All carcasses were therefore targeted dorsally and the focal impact points were the skull, thoracic spine and pelvis. Perpendicular impacts were attempted in all cases to mimic the worst case scenario with maximal transfer of collision energy; fractures are more likely with a faster impact absorption as impact loading is a factor of both force and time over which the force is applied (King 2018). Further, established tissue deformation properties for seals suggest that angle of attack has a large impact on stress-strain curves, with frontal impacts producing the greatest deformation to blubber layers (Grear *et al*. 2018).

Preliminary trials with five carcasses were conducted with a different, curved turbine blade replica, attached to the keel of the jet boat. Details of these trials and conversion factors to allow direct comparison of results to the later trials are presented in the electronic supplementary material.

2.2 Injury assessment

Each carcass was subject to post-trial CT scans (Siemens SOMATOM Scope 16 slice spiral) to provide insight into skeletal trauma. Post-mortem analyses followed to confirm fractures, identify soft-tissue damage and measure mid-sternal blubber thickness. Each case was inspected for signs of soft tissue damage associated with blunt force trauma. Injury criteria are given in table 2. Key locations for assessment were integument, visceral organs, diaphragm and observations of musculature haemorrhage. Mid-sternal blubber thickness and stomach contents were recorded to assist in interpretation of ante-mortem condition.

Pathological features of severe trauma were identified, categorised by location and tallied to provide a quantification of the extent of injury. As this experiment was carried out on dead carcases which had undergone several freeze-thaw cycles, it was not possible to assess subtle indications of collision trauma, such as morbidity or delayed mortality. Necropsy assessment was therefore restricted to identifying traumatic pathologies considered severe enough to cause immediate or assured fatality.

2.3 Statistical Analysis

To assess the effect of turbine blade speed on the probability of inducing severe trauma in seals, we modelled the presence of pathological indicators of mortality using generalised linear models (GLM) with binomial errors and a logit-link function. Each collision was coded as 0 or 1 depending upon the absence or presence of one or more pathological indicators of severe trauma associated with that collision. We used this binary variable as our response and as such were testing the correlation between known, detectable fatality and select intrinsic and extrinsic covariates. This allowed us to determine the dose-response relationship (Harris *et al.* 2018) between impact speed and severe trauma in a probabilistic framework. Discrete pathological indicators of mortality (i.e. damage which would be indicative of mortality in a living seal) were assigned based on anatomical region; we assigned injuries to specific trials based on the strike location nearest to the injury in question. Multiple spinal injuries on one individual were considered discrete if they occurred in a different region of the spine; namely the cervical, thoracic, lumbar or sacral region. Rib fractures were included as one attribute regardless of the number of fractures occurring. If multiple rupture locations or traumatic lesions were observed on the same organ, this was considered a single discrete attribute. In cases where trauma could have been the result of another pathological attribute (e.g. hepatic herniation as a result of diaphragmatic rupture), causation was not assumed, and both attributes were considered discrete. None of the carcasses demonstrated any signs of external trauma and were visually indistinct from pre-trial condition; no lesions, cuts or external bruising was visible as a result of collision trials.

Candidate variables tested in the model were collision speed, blubber thickness, sex, strike count and strike location. Strike count was given as the number of strikes that particular trial constituted for that individual and therefore had a maximum value of 3. The inclusion of this variable tested whether multiple strikes affected the likelihood of the presence of pathological indicators of mortality. Mass was initially included but was removed due to collinearity with blubber thickness. Blubber thickness was considered a more relevant metric as it provides a better proxy for animal health and blubber should act as protection from impact (Pond 1978; Iverson 2009). An interaction term between speed and blubber thickness was included to assess whether the ability of speed to describe the pathology of a collision case could be affected by blubber thickness. Model selection was undertaken using backwards, stepwise selection and comparing Aikaike's Information Criterion (AIC) values. An improved fit was determined if AIC value reduced by 2 from the previous model (Burnham & Anderson 2002).

As an example of how the results could be used in practice, the tidal prediction software POLPRED was used to generate estimates of current speeds at ten minute intervals over a one month period in a site proposed for tidal energy extraction. These current data were used to generate estimates of the blade speed assuming that the turbine stalls at a current speed of 1 $m.s^{-1}$ and reaches a maximum tip speed of 12 $m.s^{-1}$ for current speeds of 2.5 $m.s^{-1}$ and higher as demonstrated by the SeaGen tidal turbine operating in Strangford Lough, Northern Ireland (Sparling, Lonergan & McConnell 2017). This distribution could then be taken as the proportion of theoretical collision speeds between randomly moving seals and tidal turbine blades across a tidal cycle. The increase in blade tip-speed from 0 $m.^{s-1}$ to 12$m.s^{-1}$ was assumed linear from the stall to maximum current speed as turbine rotation is directly driven by the current. These values were assumed consistent with typical tidal turbine operations (Sparling, Lonergan & McConnell 2017) and model predictions were correlated with these calculated, theoretical impact speeds to determine the proportion of cases which we could be confident would result in fatality. Finally, these proportions were combined with flow speed predictions for a proposed tidal turbine array site in Scotland. These were used to estimate the proportion of the turbine blade swept area which had speeds above a determined mortality probability from the dose-response model, across a tidal cycle.

All statistical modelling and subsequent analysis was performed in R (R Core Development Team 2016)

3. Results

3.1 Trials

A total of 28 collisions were carried out at speeds ranging from 2.1 $m.s^{-1}$ to 10.34 $m.s^{-1}$. Table 1 details the speed and location of each strike along with morphometric data of the carcasses.

Table 1: Morphometrics of experimental subjects including speed and collision location for each collision trial. * indicates the collision speeds which were calculated post-hoc after impact with a curved blade. See appendix 1 for full details. All individuals were judged as sub-adults except for seals HgA, HgC and PvDV which were classed as adults. All individuals were grey seals except seal PvDV which was a harbour seal.

Seal ID	Sex	Mass	Blubber Depth	Trial Number	Collision Speed ($m.s^{-1}$)	Collision Location
TA04	m	18	30	1	4.9	Thoracic Spine
				2	5.6	Head
				3	5.2	Lower Pelvis
HJ02	m	32	23	4	5.5	Sacral Spine
				5	5.5	Thoracic Spine
JG07	f	19	14	6	6.3	Thoracic Spine
JG06	f	22	19	7	6.5	Sacral Spine
TA03	f	20	19	8	6.1	Cervical Spine
				9	6.8	Pelvis
HJ01	f	32	19	10	8.2	Sacral Spine
HJ03	m	38	24	11	7.1	Thoracic Spine
				12	7.5	Cervical Spine
JG03	f	39	22	13	5.6	Sacral Spine
				14	5.3	Cervical Spine
PvDV	m	86	34	15	8.4	Thoracic Spine
				16	8	Pelvis
				17	8	Head
HJ05	m	42	16	18	9.26	Head
				19	9.26	Thoracic Spine
HJ08	m	25	23	20	10.19	Head
				21	10.07	Thoracic Spine
JG10	m	27	18	22	10.08	Thoracic Spine
				23	10.19	Pelvis
HJ07	m	46	18	24	10.03	Thoraco-cervical spine
				25	10.34	Cervical spine
				26	10.29	Thoracic Spine
HJ09	f	26	22	27	10.19	Thoracic Spine
				28	9.98	Pelvis
HgA	m	200	16	29	2.5*	Pelvis
				30	2.5*	Skull

				31	2.2*	Thoracic Spine
				32	2.07*	Pelvis
HgB	m	52.3	22	33	2.07*	Skull
				34	2.07*	Thoracic Spine
				35	5.25*	Pelvis
HgC	m	206	47	36	5.25*	Skull
				37	5.25*	Thoracic Spine
				38	5.27	Pelvis
TA05	f	56.7	25	39	5.27	Skull
				40	5.27	Thoracic Spine
				41	5.27*	Pelvis
TA07	m	48.7	24	42	5.27*	Skull
				43	5.27*	Thoracic Spine

3.2 CT scans, radiography and post-mortem analysis

Pre-trial CT scans confirmed the absence of fractures, severe muscle haemorrhage and large organ ruptures or herniation. Post-trial analyses of the cross-sectional scans of each seal carcass revealed several skeletal injuries. Damage to the spine was observed in eleven carcasses. Spinal injuries included fractures to the lateral spinous processes and, separation and fracture of vertebrae (Fig. 2) often associated with focal muscle maceration (Fig. 3, Table 2). Broken ribs were recorded in four cases (Fig. 4) and a fractured scapula in one case (Fig. 5). No damage was recorded to the pelvis, skull or mandible in any case, despite these locations being targeted during trials.

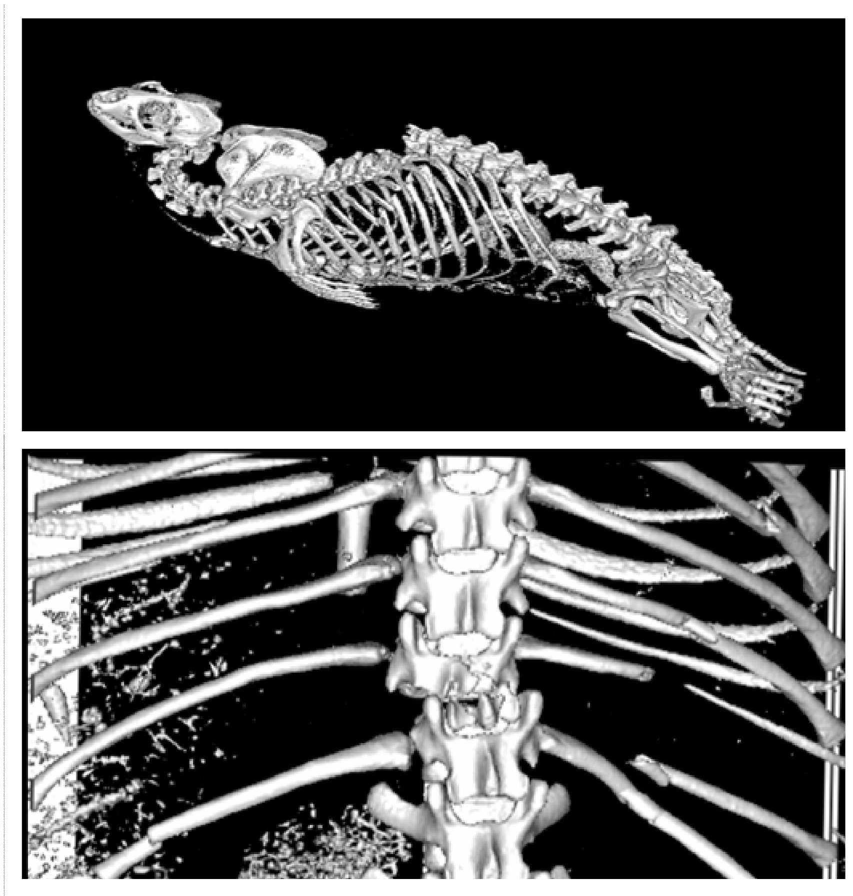

Figure 2: Separation in the thoracic vertebra of seal PvDV (above) and separation in the thoracic vertebra with associated fracture of the lateral spinous process (below). Results of trial #15 in Table 1.

Figure 3: Maceration of axial musculature around spinal fractures of seal HJ02 (left) and HJ01 (right). Results from trials #5 and #10 respectively (Table 1).

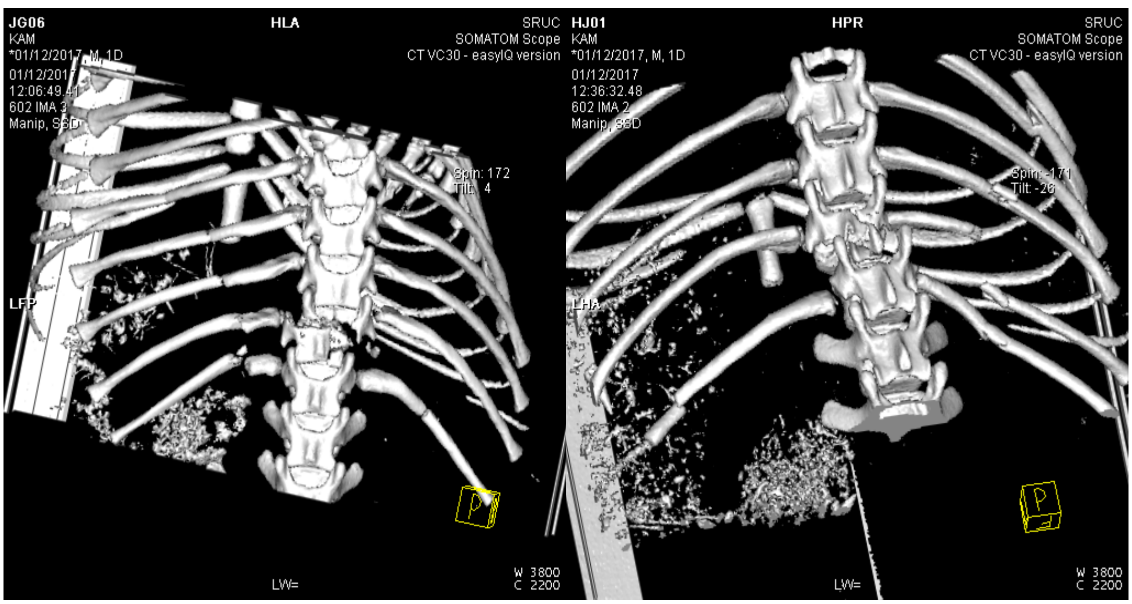

Figure 4: Fractured ribs of (left) seal JG06 and (right) HJ01. Results from trial #7 and #10 respectively (Table 1).

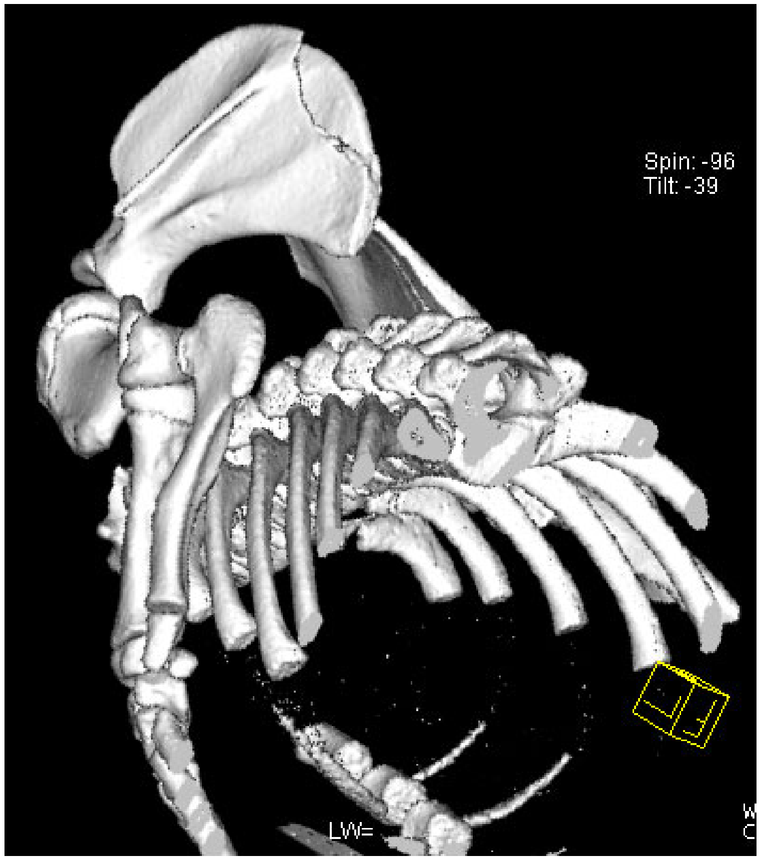

Figure 5: Fractured left scapula of seal HJ03. Results from trial #12 (Table 1).

Hepatic rupture was noted in four cases (Fig. 6), three of which were also associated with diaphragmatic rupture and herniation of abdominal organs into the thoracic cavity. Three additional cases demonstrated diaphragmatic rupture with no herniation. Pulmonary rupture was noted in two cases and cardiac rupture in one case. Liquefaction of the blubber layer was observed in the only harbour seal represented in the trials (Fig. 7). In addition, rupture of the thin mediastinum, a potentially sub-lethal indication of trauma, was noted in 5 cases.

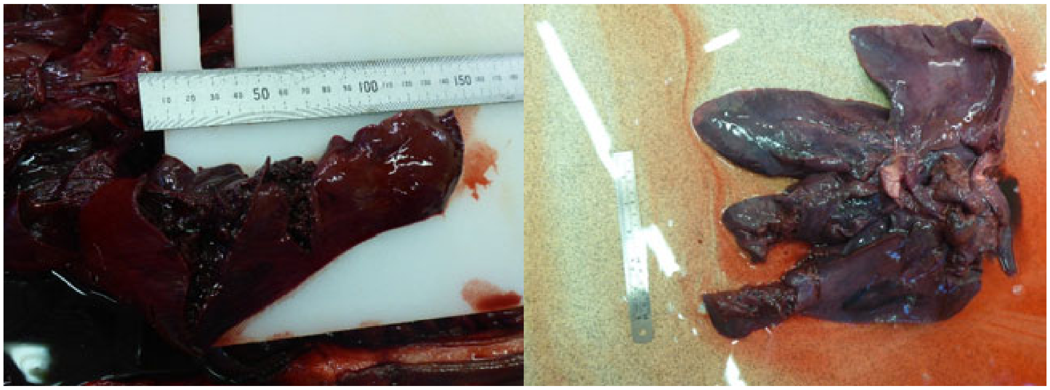

Figure 6: Ruptured liver of (left) seal HJ01 and (right) seal PvDV. Results from trial #10 and #16 respectively (Table 1).

Figure 7: Liquefaction of the blubber layer of seal PvDV. The adipose cell rupture extended ~21 mm into the blubber from the subcutis. Results from trial #15 (Table 1).

All seals were judged to have been in good physical condition prior to death with expected blubber reserves for their assumed age and varying degrees of food in the gastro-intestinal tract. Gross examinations revealed no evidence of underlying terminal disease or morbidity.

Table 2: Identification of presence (red) or absence (green) of broad pathological indicators of mortality for each seal carcass. Seals are arranged from slowest mean collision speed (top) to fastest (bottom).

Seal ID	Mean Collision Speed ($m.s^{-1}$)	Diaphragmatic Rupture	Spinal Fracture	Fractured Rib(s)	Liver Rupture	Liver Herniation	Pulmonary Rupture	Cardiac Rupture
HgB	**2.1**	green	green	green	green	green	green	green
HgA	**2.4**	green	green	green	green	green	green	green
TA04	**5.2**	green	green	green	green	green	green	green
HgC	**5.25**	green	green	green	green	green	green	green
HJ02	**5.5**	green	green	green	green	green	green	green
JG03	**5.5**	green	red	green	green	green	green	green
JG07	**6.3**	green	red	green	green	green	green	green
JG06	**6.5**	green	red	red	green	green	green	green
TA03	**6.5**	green	green	red	green	green	green	green
HJ03	**7.3**	green	red	green	green	green	green	green
PvDV	**8.1**	red	red	red	red	red	red	red
HJ01	**8.2**	red	red	red	red	green	green	green
HJ05	**9.26**	red	red	red	red	green	green	green
JG10	**10**	green	red	green	green	green	red	green
HJ09	**10.1**	red	red	red	red	red	green	green
HJ08	**10.2**	red	red	red	green	red	green	green
HJ07	**10.2**	red	red	green	red	red	green	green

3.3 Dose-response relationship

The best fit binomial GLM retained the covariates speed of collision (β= 1.23, s.e. = 0.44, z = 2.76, $p<0.05$) and location of the strike (factor=Thoracic Spine, β= 4.16, s.e.=1.77, z=2.35, $p<0.05$) (Table 3). The interaction term between speed and location, and blubber depth did not improve model fit and were therefore removed from the final model. Random effects did not improve model fit and so were discarded from the final model.

Strike location explained a significant amount of the variation in the data; null deviance (21.9, 18 d.f) decreased to a residual deviance of 8.9, 15 d.f with the inclusion of strike location, blubber and speed as covariates. A second model was subsequently fit to data from strikes to the regions which demonstrated severe trauma (Thoracic spine). The best fit model through backwards stepwise selection retained the covariates of speed of collision ($\beta = 1.13$, s.e.= 0.35, z=3.23, $p<0.05$) and blubber depth ($\beta = -0.35$, s.e. = 0.15, z=-1.008, $p >0.05$, Table 3). Model predictions suggest that the probability of severe, fatal injury exceeds 0.5 at 5.1 $m.s^{-1}$ (95% CIs: upper=3.2 $m.s^{-1}$, lower=6.6 $m.s^{-1}$, Fig. 8). We evaluated the influence of each data point (*i*) using a graphical assessment of Cook's Distance (D_i). No Cook's Distances were noticeably different from the median, with no values above 0.5. This is generally considered indicative of no overt influence of any single data point (Chatterjee & Hadi 2015).

Probability of severe trauma resulting from collisions with the thoracic spine decreased with increasing blubber depth (Fig. 9) although the confidence intervals around the model predictions were high.

Table 3: Backwards stepwise selection of model parameters using AIC. Covariates are denoted by Sp (speed of collision), L (location of strike), Sx (Sex), Sc (strike count) and B (Axial blubber depth). A colon (:) denotes an interaction term between covariates. The first line of each section represents the maximal model with all covariates and interactions included, and therefore have a ΔAIC of 0. Grey shading indicates the best-fit model in that selection.

Model Data	Covariates	AIC	ΔAIC
All Locations	Sp:L+Sx+Sc+B	33.46	0
	Sp:L+Sc+B	28.66	-4.8
	Sp:L+B	24.45	-9.01
	Sp:L	22.52	-10.94
	Sp+L+B	22.87	-10.59
	Sp+L	20.98	-12.48
Thoracic Spine	Sp:B+Sx+Sc	24.92	0
	Sp:B+Sx	22.81	-2.11
	Sp:B	18.34	-6.58
	Sp+B	16.4	-8.52
	Sp	14.52	-10.4
	B	26.74	1.82

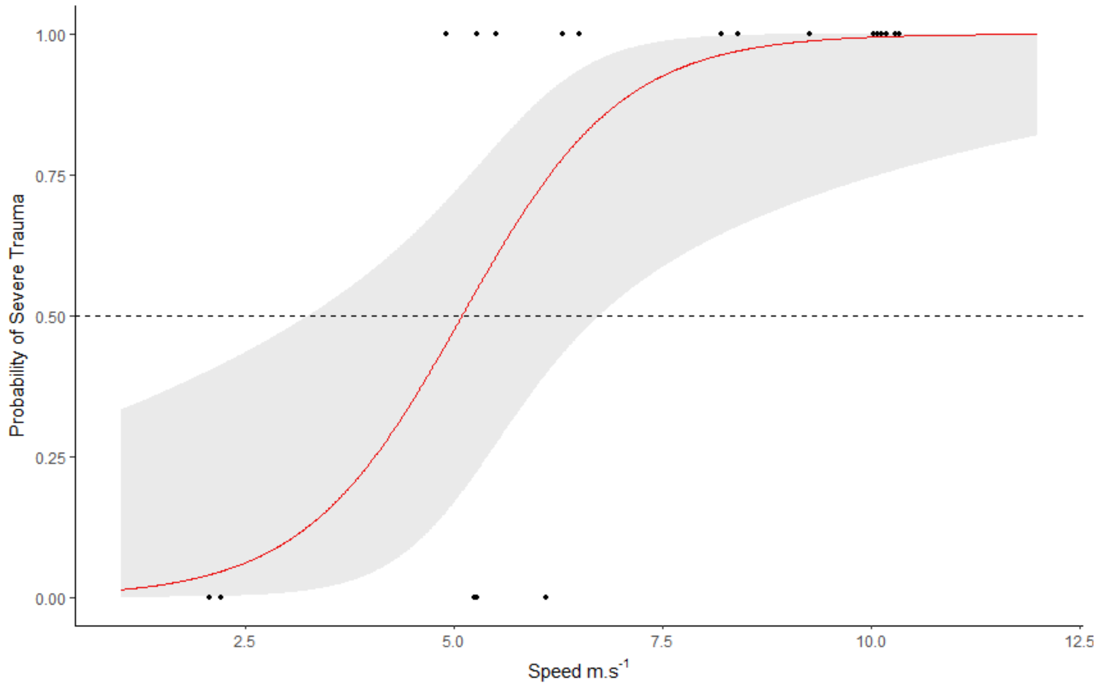

Figure 8: Probability of severe trauma as a function of blade impact speed of collision. Fitted values (red line) are given with associated bootstrapped 95% confidence intervals (grey shaded area). The horizontal black dashed line indicates the 50% probability of severe trauma. Probabilities are estimated using an assumed blubber depth of 21.5 mm; the mean mid-sternal blubber thickness of seals used in these trials.

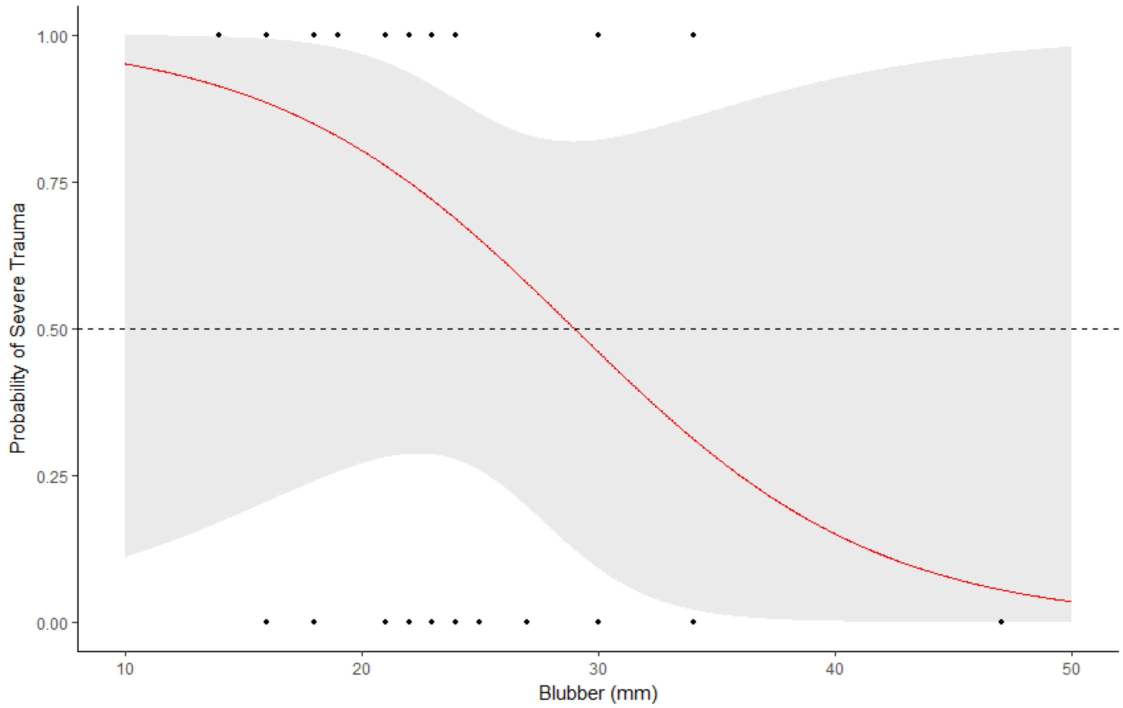

Figure 9: Probability of severe trauma as a function of blubber depth. Fitted values (red line) are given with associated b21ootstrapped 95% confidence intervals (grey shaded area). The horizontal black dashed line indicates the 50% probability of severe trauma. Probabilities were estimated using a constant collision speed of 6.7 m.s-1; the upper CI for a 50% probability of severe trauma from model predictions of the effect of collision speed to a carcass with a mid-sternal blubber thickness of 21.5 mm.

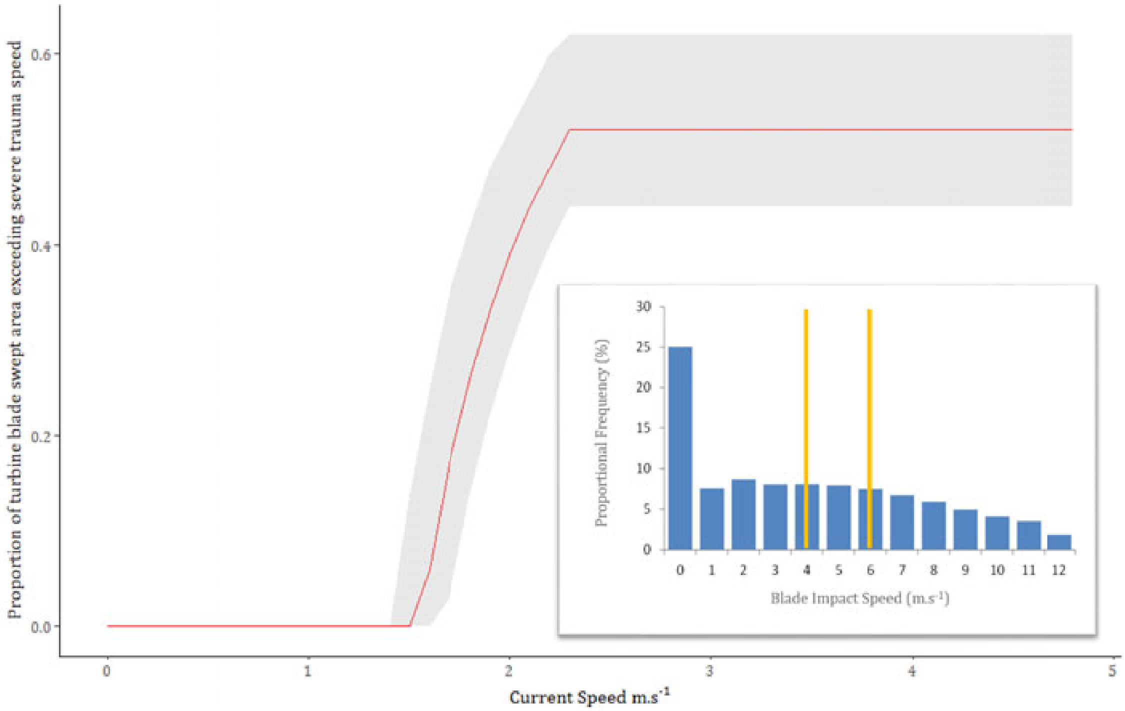

Figure 10: Proportion of a blade swept area estimated to cause severe trauma. The proportion is plotted as a function of current speed assuming a cut-in current speed of 1 m.s^{-1} and a constant blade tip speed in current speeds >2.3 m.s^{-1}, as demonstrated by the SeaGen device in Strangford Lough, Northern Ireland (Joy *et al.* 2018). The mean threshold for severe trauma is shown by the red line and bootstrapped 95% confidence intervals are shown by the grey shaded area. The panel plot shows a frequency distribution of blade impact speeds over a full lunar cycle. Yellow bars indicate 95% confidence intervals around the estimate of impact speed resulting in severe trauma.

4. Discussion

This study provides the first empirical estimates of the likelihood of severe trauma to a marine mammal as a result of collisions with tidal turbine blades at a range of speeds. We have demonstrated that collision speed is an important predictor of physical trauma. We then predict that a large proportion of potential collisions would occur at speeds below those likely to result in severe skeletal injuries. Other potentially fatal injuries that were identified (e.g. cardiac rupture, liver herniation) only occurred at collisions speeds markedly higher than the threshold speeds for severe skeletal injuries (Table 2). However, given the limitations in reliably assessing more subtle trauma in carcases which have undergone freeze-thaw cycles, it should not be interpreted that collision speeds below these thresholds are benign.

Model predictions highlight physiological parameters as marginal predictors of the severity of collisions when compared to the energy imparted by a collision, and therefore the risk is reasonably constant across the range of likely sizes and body conditions of pinnipeds in UK waters. Given the paucity of data on the impacts of tidal turbines on the marine ecosystem, this study addresses a major uncertainty and provides regulators and industry with information to establish and refine mitigation measures to avoid potentially deleterious effects of the tidal industry.

The potential for collisions between marine predators and renewable energy devices has been theoretically assessed through a number of different approaches (Wilson *et al.* 2006; Grant, Trinder & Harding 2014; Band *et al.* 2016). However, limited by the paucity of information on the potential for mortality during collisions, most have tended towards cautionary approaches whereby mortality is assumed to be the only outcome of any collision event. Band *et al.* (2016) demonstrated that imposing a mortality threshold would have a significant effect on the resulting estimate of removal from local populations of seals. When compared to the frequency distribution of collision speeds at an example tidal array site, the model predictions suggest the impact speed threshold of severe skeletal trauma would result in at least 48% of predicted collisions being immediately fatal (Fig. 10). When interpreting these predictions, it is important to bear in mind that collisions were with the section of the blade with the narrowest and therefore most damaging part (the tip); this is due to the concentration of energy transfer through the skin and blubber layers. Further, they only encompassed strikes to the dorsal region of the seal carcasses and do not address a probable decrease in the likelihood of skeletal injury with strikes to the ventral surface. Therefore, the results should be interpreted with these caveats in mind.

Due to the current assumption in collision risk models that all collisions will be fatal, we can conclude that previous mortality estimates derived from CRMs could justifiably be adjusted to account for the mortality threshold measured here. It is important to highlight that we do not conclude that 52% of the collisions were benign (discussed below), only that they did not result in the catastrophic trauma identified in this study. We do not suggest that all fatal injuries are covered under this framework but indicate which impact speeds would almost certainly result in severe trauma should they occur. The dose-response curve does not therefore indicate survival of all cases below the threshold, but rather highlight the number of cases we can confidently assume would result in fatality. Furthermore, the results in this study pertain to phocids (primarily juvenile grey seals) and care should be taken when extrapolating out to other taxa and age-classes. CRMs estimate collisions under the assumption of randomly moving seals colliding with a tidal turbine blade and largely ignore the potential for a change in seal distribution across a tidal cycle (Thompson *et al.* 1997; Zamon 2001), the potential for close-range avoidance (Hastie et al, 2017), and the change in distribution due to the presence of tidal turbines (Sparling, Lonergan & McConnell 2017). Nevertheless, this mortality threshold is likely to have a significant effect on collision estimates and subsequent assessments of the consequences for populations of seals.

From the tidal energy industry perspective, these results have important implications for both mitigation and consenting. It has been demonstrated that harbour seals show avoidance behaviours at scales of tens to hundreds of metres (Hastie *et al*. 2017; Sparling, Lonergan & McConnell 2017), but information on close range evasion of the rotating blades is currently lacking. Information on the consequences of interaction are therefore critical for estimating potential mortality risks. Our results suggest that for a turbine operating at a maximum tip-speed of 12 $m.s^{-1}$, the number of fatal collisions as previously predicted through collision risk models could be reduced by as much as 52%. However, caution must be taken when applying these corrections as this study only addressed immediately fatal injuries.   Further work is needed to assess potential lethal effects of injuries due to slower collisions that were not apparent in this study.

Our results also suggest that the demographics of seal populations around an array site is an important factor to consider as intrinsic characteristics such as mass or blubber thickness influence an individual's ability to withstand blunt-force trauma. These results could be used to design mitigation or monitoring strategies around turbine sites which could be more cost-effective if they only needed to be enforced during periods where collisions will be fatal; studies have shown that seal presence in a tidal channel is influenced by tidal state (Zamon 2001; Hastie *et al.* 2016). Therefore, periods of exhaustive monitoring, and mitigative shutdown should seals be detected, could be imposed to reduce the likelihood of interactions during periods of high seal usage.

Quantification of collision consequences in the marine environment have been largely limited to ship strikes in large cetaceans and this bears little comparability to the physical attributes of smaller pinnipeds. However, there is literature detailing the relationship between automobile and sporting impact speeds, and injury in humans. (Watanabe *et al.* 2012) used modelled collisions between pedestrians and automobiles to demonstrate that impact speeds of 20 Km/h (5.5 $m.s^{-1}$) did not result in any severe injuries including skeletal fractures and soft tissue injuries to major organs or the brain. However, at higher speeds, mass of the subject and location of the strike became an important predictor of injury. This is broadly analogous to our findings that at speeds lower than 5.6 $m.s^{-1}$ collisions do not cause severe pathological injury regardless of intrinsic attributes or strike location. Further, we noted that at higher speeds blubber reserves offer a protective effect. This inference must be treated with caution however as the decline in probability of severe injury includes wide confidence intervals which span 0.5 at blubber depths above 20 mm. Theoretical models of interactions between larger marine mammals and tidal turbines have suggested that impacts may be benign across all scenarios. Carlson *et al.* (2014) suggested adult southern resident killer whales would not succumb to any injuries caused by collision with the OpenHydro tidal turbine, a ducted, multi-blade turbine in Puget Sound, Washington, assuming collisions with the skull were worse case scenarios. As our results demonstrate that the probability of traumatic injuries decreases with increasing blubber thickness, it appears likely that size and/or condition is an important consideration when determining the outcome of a collision between a tidal turbine and a marine mammal.

Only carcasses which were known to be recently deceased were used in this study and we were careful to not over-interpret the consequences of collisions to soft-tissue due to the potential confounding of the freeze-thaw process. The freeze-thaw process can generate pathological artefacts which can be confused with the impact of trauma, such as pseudo-bruising of subcutis; the resemblance of haemorrhage in the thoracic cavity, pericardial sac and abdominal cavity; apparent subcapsular renal haemorrhage; pseudo-contusions of the brain; apparent haemorrhage from the nares; and blood-staining of the anterior ocular chamber (Roe, Gartrell & Hunter 2012). Consequently, many likely sequelae from collisions involving live animals could not be confidently evaluated in this experiment. Nonetheless, the assessment indicators chosen, of severe catastrophic trauma incompatible with life, were felt to provide robust upper bounds for quantifying the impact of blade collisions using cadavers. The freeze-thaw process is also known to have a significant impact on the structural rigidity and stress/strain features of soft tissue, particularly skin and blubber (Grear *et al.* 2018). The protective properties of blubber may be hindered by the freezing process, providing less resistance to direct impact . However, studies have shown there is limited evidence to suggest a significant structural change to blubber as a result of freezing (Grear *et al.* 2018) and regardless, this would render the presented results additionally conservative. An increased sample size using un-frozen carcasses for the empirical testing of the pathological consequences of collision to both the skeletal structure and soft-tissue, representing a wider range of demographics, species and fitness states would help resolve the relationship between animal size, collision speed and mortality.

Post-trial CT scans revealed no evidence of skull fractures. This contrasts with the human literature where collisions with a range of shapes have been shown to produce fractures at much lower speeds (Hodgson & Thomas 1973; Yoganandan *et al.* 1995; Delye *et al.* 2007). This may be related to the differing skull thicknesses of humans compared to the seals in this study; mean frontal skull thickness of the seals here was 6.9 mm (±0.8) whereas adult human skulls have mean frontal thicknesses of between 5.7 mm and 6.3 mm respectively (Mahinda & Murty 2009). It has been demonstrated that frontal skull fracture in humans can be induced for energies of between 22-24 J (Delye *et al.* 2007) and at impact speeds as low as 2.73 $m.s^{-1}$ (Hodgson & Thomas 1973). We demonstrated that seal skulls are capable of withstanding collisions to the frontal region with a turbine blade at speeds of up to 10.1 $m.s^{-1}$. Deyle *et al.* (2007) suggested the disparity in forces required to fracture embalmed and non-embalmed skulls could be a result of energy absorption by the scalp. Seals have considerably thicker scalps than humans which may explain the higher resistance to frontal skull fracture as full compression of the tissue occurs at a higher impact energy. Energy will also be lost in these collisions through rotation of the head and therefore it is possible that a combination of morphology and increased spinal flexibility in seals may reduce the likelihood of skull fracture. Strike location on the skull is also likely to have an effect as resistance to fracture varies across the skull with strength, decreasing from the posterior skull to the lateral and frontal regions (Hodgson & Thomas 1973; Yoganandan & Pintar 2004). These results therefore likely exhibit the worst case scenario for skull fracture and give further justification for the lack of skull damage at the speeds presented.

The experimental procedure presented in this study was not able to assess the effects of traumatic brain injury (TBI), specifically concussion and axonal strain injuries. The combined effects of autolysis and the freeze-thaw process precluded the assessment of TBI due to possible mis-identification of traumatic injury (Roe, Gartrell & Hunter 2012). This presents a potential issue as cases of concussion considered mild in humans can cause symptoms that in seals (as a diving mammal) could lead to drowning. Omaya & Hirsch (1971) demonstrated that the tolerance to concussion scales with the ratio of brain mass to head mass and that the reduction in this fraction in chimpanzees compared to humans and rhesus monkeys resulted in a higher tolerance to TBI. Coupled with a thicker scalp, animals with more 'padding' are more resistant to TBIs resulting from either angular or linear acceleration. We can therefore assume that due to their relatively large skulls and small brains, and the capacity for some cushioning from a thin blubber layer on the head, seals may be relatively more resistant to TBIs. Further, the location of the strike and the size of the animal's skull and scalp will have an effect on whether a TBI is sustained. However, this remains an area which requires further research and the results of this investigation should not be considered categorical evidence of severity of brain injuries, or indeed any soft tissue damage, as a result of collisions with tidal turbines.

In summary, this work has provided robust evidence that immediate, severe skeletal injury would occur during all collisions between seals and tidal turbine blades at impact speeds above 6.6 $m.s^{-1}$ with no pathological indicators of severe trauma detectable at collision speeds below 5.5 $m.s^{-1}$. A dose-response curve fitted to these data estimate a lower 95% confidence interval for severe trauma of 4.4 $m.s^{-1}$. In the worked example for a typical, horizontal axis tidal turbine, 48% of the potential collisions are estimated to be at speeds greater than this threshold. This has potentially major implications for regulators assessing the environmental risks associated with the tidal energy industry. These results can be adapted to suit different tidal regimes and turbine designs. Given that blade speed is a major factor in determining likelihood of severe injury, design considerations that reduce blade speed could avoid these problems. Additional work to determine the extent of soft tissue damage and potential concussion injuries would reduce the uncertainty surrounding these estimates,

Authors Contributions

J.O, D.T, S.M and G.H. conceived the study and designed the methodology; J.O. and S.M. conducted the trials; J.O. and A.B. conducted post mortems, J.O. analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Data Accessibility

Data available via the Dryad Digital Repository: https://doi:10.5061/dryad.8gb1n31 (Onoufriou et al. 2019).

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