Electronic supplementary material

How sailfish use their bills to capture schooling prey

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Text

Bill structure. The bill of the sailfish specimen was photographed using a photo camera [Canon EOS 5DII with Canon 100 mm Macron EF Lens (1:2.8)], (Figure S1A,B,D) and a combination of microscope (Leica MZ6, 16X) and photo camera (Panasonic Lumix T210) (Figure S1C). The macro and microstructure of the bill are shown in Figure S1. The lateral sections and part of the underside of the bill are covered with irregular denticles that create an abrasive surface which may serve to facilitate prey capture during tapping and for injuring prey during slashing.

Kinematic performance of bill motion. The maximum speed measured at T_{sf} corresponds, for a 19-cm sardine, to approximately 33 body lengths s^{-1} which is 3.4-times faster than the maximum calculated swimming speed for a 19 cm long fish [i.e. 1.8 m s^{-1}, based on the equation [1]: Maximum speed = 0.4 + 7.4 × Body length]. The maximum speed at T_{sf} is reached in a very short time (52 ± 22 ms) and its acceleration is comparable to the highest values found in the literature on fish swimming motions, which range approximately from 20 to 150 m s^{-2} [2-4]. Therefore, based on speed and acceleration performance alone, sardines are not expected to be able to avoid a slash. However, reaction time of the prey needs to be also taken into account in order to assess their ability to avoid being hit by the bill (see below).

Turning rate data were compared with literature values for other aquatic vertebrates. Turning rate in fish and other aquatic vertebrates decreases with body length [2, 5]. Our data show that a 1.8 m long sailfish (total length including the bill: 180 ± 27 cm, n = 5) with a 0.3 m bill "extension" (30±1.5 cm, n = 5) is able to perform a mean turning rate (i.e. 575 degrees s^{-1}) comparable to that expected in a 1.5 m fish [i.e. 470 degrees s^{-1} based on previous work on scaling in aquatic vertebrates ($\log TR_{mean} = -0.84 \log \text{Body length} + 4.5$) [2]). This suggests that the additional drag caused by bill's thin extension during slashing has little effect on overall turning rate performance.

Using morphological data from other Istiophorid species and the relationship between mean turning rates and body length [2], we estimated the mean speed of the bill tip (i.e. at T_{sf}) for11 species of Istiophirods (Table S1), based on the speed of a segment (head length, i.e. the head inclusive of the bill, see Table S1) rotating at an angular velocity corresponding to the estimated turning rates. The results suggest that most Istiophorid species are potentially capable of reaching similar T_{sf} speeds to those measured in sailfish (mean slashing speed at T_{sf} = 4.25±0.33 m s^{-1}; N=15). Interestingly, the highest T_{sf} speeds would be reached in the slashes of swordfish, largely a consequence of possessing the longest bill (relative to body length) compared to all other Istiophorids. For example, compared to Atlantic sailfish, swordfish have a lower estimated turning rate (caused by their larger size), which is more than compensated for by having a longer bill, producing as a result a higher T_{sf} speed (Table S1). Comparison among the morphological features of Istiophorids also shows that the fineness ratio (FR) of marlins and swordfishes is very close to the predicted value for minimizing drag (4.5, from [1]), while sailfishes and other Istiophorids have a higher FR. Inter-specific differences in FR, as well as differences in the size of the dorsal fin, suggests that swimming behaviour may differ among Istiophorids both in terms of cruising and bursting, and therefore it is possible that their hunting strategies may also differ.

Expected reaction times of sardines. Based on speed comparisons between the maximum speed expected in sardines and the speed of the bill tip, avoidance of the slash by the sardines appears unlikely. Sardines were not observed to react in time to swim away from a slashing bill, therefore additional consideration of the reaction times expected in sardines may be more relevant. While the escape reaction time of this species of sardines is not known, work on other clupeids shows that the minimum reaction time is approximately 30 ms and that the execution of the first fast muscle contraction takes another 20-50 ms [6]. Therefore a reasonable time-estimate for the sardine to be able to displace themselves away from the impact area, is 50-80 ms. Within this time frame, the tip of a slashing bill (moving at approximately 6.2 m s^{-1}) can cover 31-50 cm. Therefore, avoidance of a slashing bill would require the fish to create a "vacuole" around it with a diameter > 62 cm which was not observed in any of our video footage.

Prey response to predatory attack.

Comparing target and control fish: During the pre-bill contact phase there was no difference in overtaking behaviour between target and control fish ($p > 0.05$, Figure 3B main text) but the target fish had a higher tail beat frequency than the control fish, though the absolute difference was small (target fish: 9.4 Hz; control fish: 8.4 Hz; $p = 0.006$, Figure 3B main text). Therefore when the sardines were being chased by the sailfish, but the bill had not been inserted in the school yet, individuals in the rear of the school tended to swim faster than control ones. However, in the bill-contact phase (i.e. when the bill is inserted into the school) there were no differences, neither in overtaking nor in tail beat frequency between target and control fish ($p > 0.05$ for both cases, Figure 3B main text). Therefore prey did not show any avoidance response to the insertion of the bill into the school. During the post-bill contact phase, an avoidance reaction was observed because the target fish had a higher tail beat frequency and a higher overtaking behaviour than the control fish (all $p < 0.001$, Figure 3B main text).

Comparing across attack phases: When comparing across the three different phases, there was no change in tail beat frequency or overtaking behaviour between the pre-bill and bill-contact phases for both target and control fish (all $p > 0.05$). This confirms that, upon insertion into the school, the bill does not cause any apparent reactions in the prey. After a slash, however, the target fish had increased values for both behaviours (i.e. a higher tail beat frequency and a higher overtaking behaviour) compared to the pre-bill contact and bill-contact phases (all $p < 0.01$, Figure 3B main text). The control fish had a higher tail beat frequency in the post-bill contact phase than in the pre-bill contact and bill-contact phase ($p < 0.05$, Figure 3B main text) but there was no difference in overtaking behaviour (all $p > 0.05$, Figure 3B main text). Therefore, sardines react to the bill only after the slashing event.

Estimation of prey swimming speeds.

The tail beat frequency of sardines was used to estimate their swimming speed during the pre-bill contact ($U_{b\text{-}c}$) phase based on the equation[1]:

$$\text{Swimming speed} = \text{body length} \times \text{stride length} \times \text{tail beat frequency}$$

where stride length is defined as the fraction of body length a fish can swim during one full tail beat. Body length (L_B) = 19 cm; stride length = 0.7 L_B, based on typical values of a carangiform swimmer [1], and tail beat frequency (TBF) was measured from the videos.

The swimming speeds of target sardines, estimated during the pre-bill contact, bill-contact and post-bill contact phases, were $U_{pre\text{-}b} = 1.25$ m s^{-1}, $U_{b\text{-}c} = 1.17$ m s^{-1} and $U_{post\text{-}b} = 2.18$ m s^{-1}, based on TBFs of 9.4 ± 2.1 Hz , 8.8 ± 2.5 Hz, and 16.4 ± 3.8 Hz, respectively.

Table S1

Common name	Scientific name	Total length TL (cm)	Body length BL (cm)	Head length (%TL)	Bill length L_{BILL} (% BL)	Body depth (%BL)	Body fineness ratio	Head fineness ratio	Bill shape at 0.5 L_{BILL}	Mean turning rate (deg s^{-1})	Mean slashing speed at T_{sf} (m s^{-1})
Atlantic Sailfish	*Istiophorus albicans§*	**240** (315)	**194** (255)	30.6	23.4	12.7	6.91	1.33	0.63*	**378** (301)	**4.84** (505)
Pacific Sailfish	*Istiophorus platypterus§*	**270** (348)	**221** (285)	31.3	22.2	14	6.25	1.61	0.68	**339** (274)	**5.01** (5.21)
Blue Marlin	*Makaira nigricans*	**290** (500)	**233** (401)	32.4	24.6	17.3	4.76	1.41	0.62	**325** (205)	**5.33** (5.81)
Striped Marlin	*Kajikia audax*	**290** (420)	**230** (333)	30.4	26.1	13.2	5.25	1.15	0.68	**328** (240)	**5.04** (5.35)
Black marlin	*Maikaira indica*	**380** (465)	**307** (476)	29.9	23.7	16.7	4.54	1.06	0.72	**257** (217)	**5.01** (5.27)
White marlin	*Kajikia albida*	**210** (300)	**168** (240)	31.5	25.3	10.4	5.88	1.56	0.62	**428** (317)	**4.94** (5.23)
Shortbill spearfish	*Tetrapturus angustirostris*	**190** (230)	**174** (210)	23.1	9.3	11.1	7.14	1.75	0.64	**415** (353)	**3.18** (3.28)
Longbill spearfish	*Tetrapturus pfluegeri*	**165** (255)	**137** (211)	27.8	20.4	11.1	6.66	1.61	0.62	**507** (353)	**4.05** (4.35)
Mediterranean spearfish	*Tetrapturus belone*	**200** (240)	**183** (220)	25	8.9	16.2	7.33	1.92	--	**397** (340)	**3.46** (3.56)
Roundscale spearfish	*Tetrapturus georgii*	**181** (184)	**155** (157)	28.4	16.5	18.4	5.42	2	--	**456** (450)	**4.09** (4.10)
Swordfish	*Xiphias gladius*	**300** (455)	**217** (329)	53.2	38.2	13.9	4.35	1.31	0.34	**344** (243)	**9.60** (10.3)

Table S1. Comparative morphology and estimated slashing performance in 11 species of billfishes.

Comparative morphology and estimated slashing performance in 11 species of billfishes. Numbers in bold represent common values, while numbers within brackets represent values for maximum length specimens. Total length (TL) was measured from the tip of the bill to the end of tail (based on www.fishbase.org). Body length (BL) was measured from the point where the front of the head meets the base of the bill, to the end of the tail (based on measurements from photos of specimens in www.fishbase.org). Head length (HL) was measured from the tip of the bill to the posterior end of the operculum (based on www.fishbase.org). Bill length (L_{BILL}) was measured from the tip of the bill to the point where the front of the head meets the base of the bill (based on measurement from photo of specimen in www.fishbase.org). Body depth was calculated as body length/ maximum body height (based on www.fishbase.org). Body fineness ratio was calculated as body length / body depth. Head fineness ratio was calculated as (HL-L_{BILL}) / maximum head height. Bill shape was calculated as bill depth / bill width at 0.5 L_{BILL} (from [7] except for *, calculated using one dead specimen from the present study). Turning rate was calculated based on BL following [2], (log TR_{mean}= -0.84log Body length + 4.5). Mean linear speed of bill tip was estimated from head length and mean turning rate (see text for details). (§) Values for *Istiophorus albicans* and *Istiophorus* *platypterus* are reported as two separate species [7], although phylogenetic analyses of molecular data from mitochondrial and nuclear gene sequences suggests that there is no genetic evidence to support recognition of two separate species of sailfishes [8].

Figure S1

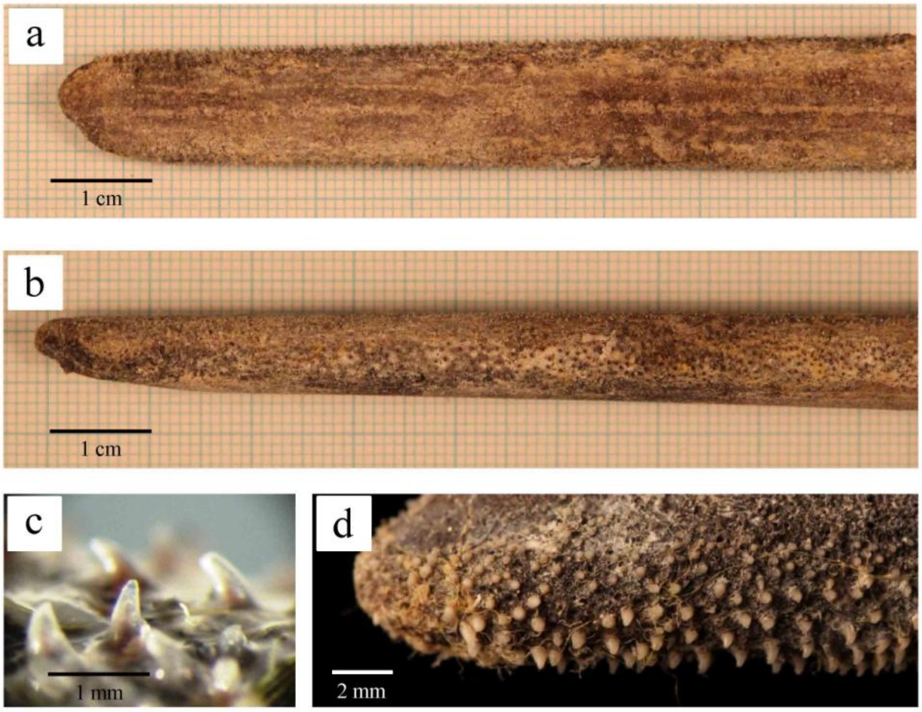

Figure S1. The tip of the bill of a local sailfish specimen.

(a) Bottom view of the tip of the bill, (b) lateral view, (c) and (d) the denticles on the side of the bill. At 5 cm from the tip of the bill the width was 1.3 cm and the height 0.9 cm.

Captions for supplemental movies

Movie S1. Slow-motion HS video of a slashing sequence.

A slashing sequence of 0.43 seconds (103 frames: recording rate 240 fps; playing rate 30 fps). In the final frames, the bill makes contact with at least 5 sardines and the scales from injured fish can be clearly seen. Behavioral states from the Markov chain are annotated on the video.

Movie S2. HD video of two tapping events.

Video of two tapping events in succession (135 frames; recording rate 30 fps). The first tapping event (frame 14) is unsuccessful, while the second one (frame 90) leads to a successful prey capture. Behavioral states from the Markov chain are annotated on the video.

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