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FISH-INSPIRED SEGMENT MODELS FOR UNDULATORY STEADY SWIMMING

SUPPLEMENTARY INFORMATION

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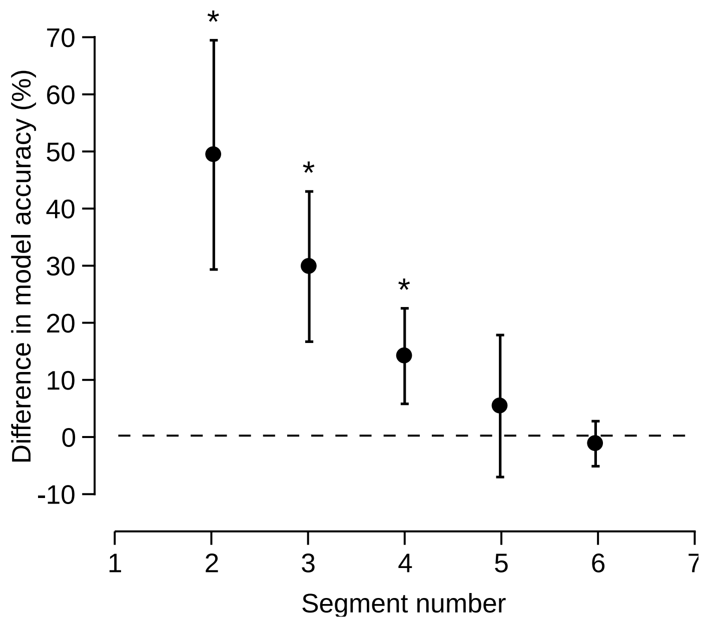
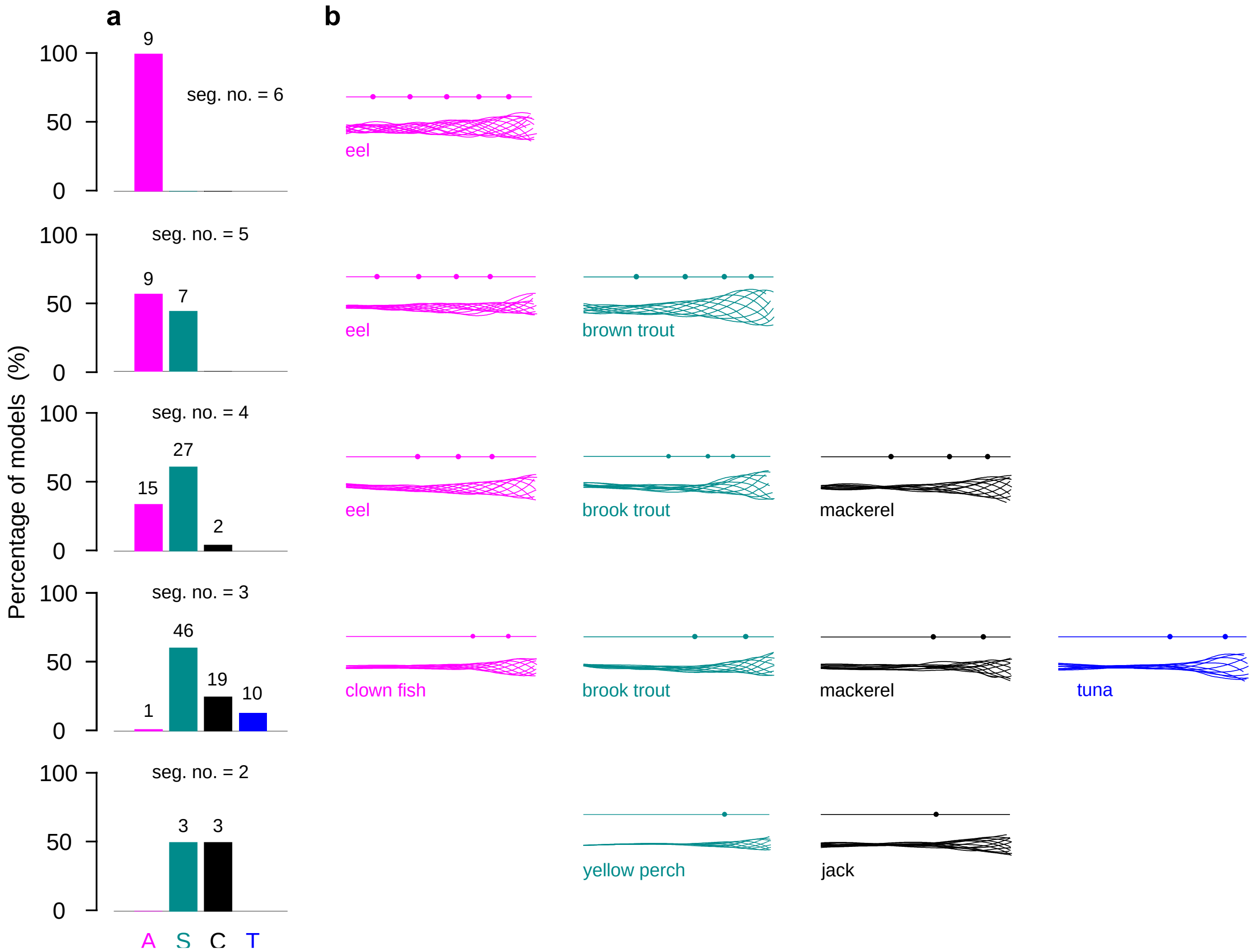
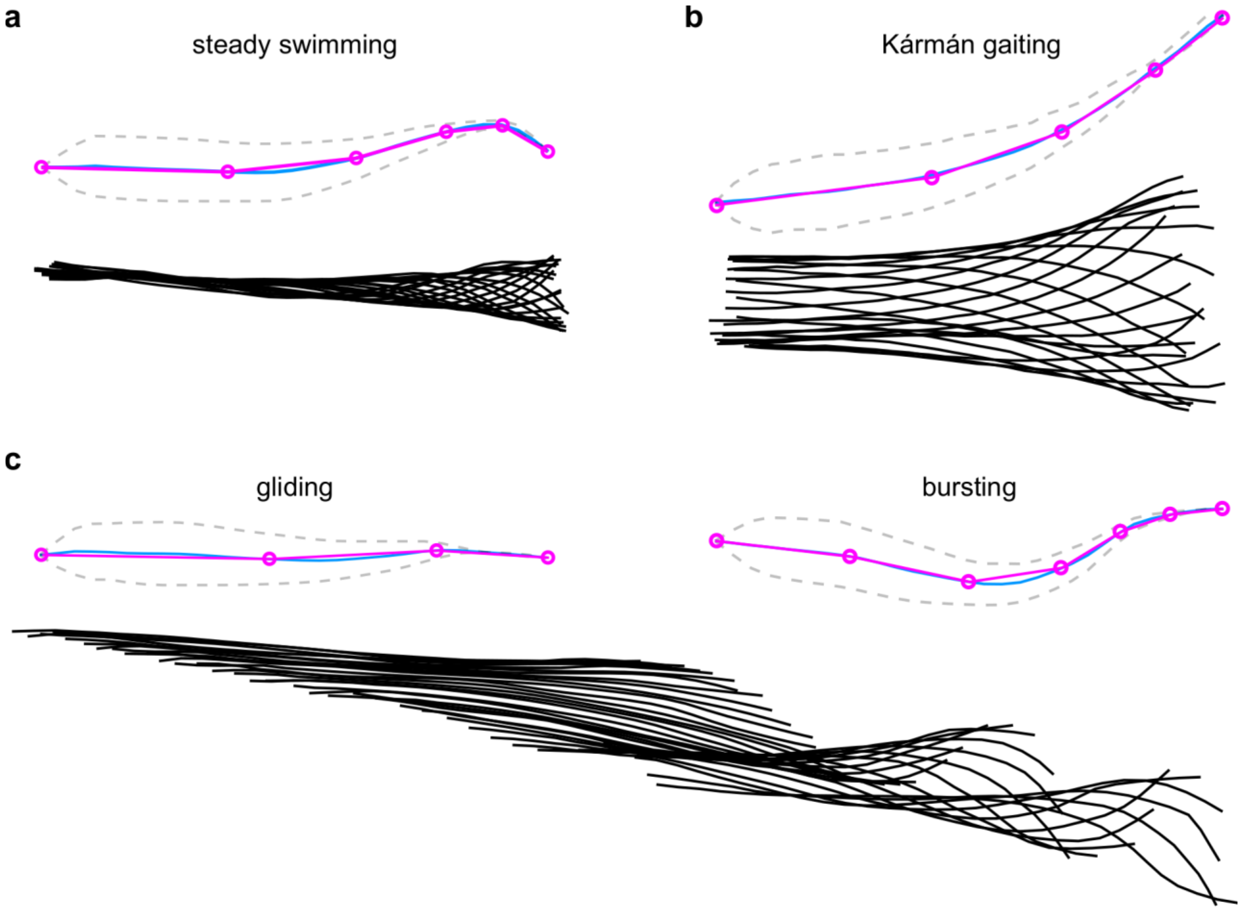
Supplementary figures and tables



Supplementary figure 1. Comparing the performance of SGM models to equal-length segment models. Mean difference in performance across two, three, four, five and six-segment models. Vertical error bars indicate one standard deviation from the mean. Horizontal dashed line shows the baseline where the performance of the SGM model is equal to the performance of the equal-length segment model. Marker * indicates data points which are higher than the baseline at significance level, $p < 0.01$.



Supplementary figure 2. **a.** Bar charts show the percentage of models distributed across swimming modes for SGM models with two, three, four, five and six segments (from bottom to top): A, anguilliform (magenta); S, sub-carangiform (teal); C, carangiform (black); T, thunniform (blue). The actual number of data points is also given on top of each bar. **b.** Actual midlines of one representative fish from each swimming mode (anterior to posterior is from left to right). Model segment configuration with joint positions (filled circles) is also shown on top of each midline data.



Supplementary figure 3. Segment configuration of SGM models of a rainbow trout (L = 23 cm) during (**a**) steady swimming at 2 L s^{-1}, (**b**) Kármán gaiting behind a half D cylinder (diameter = 5 cm), and (**c**) bursting and gliding. The incoming flow speed was 2 L s^{-1} during Kármán gaiting and burst and gliding. Burst and gliding midlines were split into two groups to obtain one model for bursting and one model for gliding. For each behavior, a silhouette of fish for one snapshot (grey) and superimposed SGM model (orange) are shown. Actual midlines (black) used to obtain the models are also shown at the bottom. This dataset is provided by the Liao Lab in addition to the datasets described in the Methods.

	j_1	j_2	j_3	j_4	j_5
2-segment	0.67±0.06				
3-segment	0.54±0.07	0.81±0.05			
4-segment	0.36±0.09	0.64±0.06	0.83±0.04		
5-segment	0.26±0.06	0.48±0.08	0.67±0.07	0.83±0.06	
6-segment	0.18±0.04	0.36±0.04	0.53±0.05	0.69±0.05	0.85±0.05

Supplementary table 1. Mean joint positions of the SGM models along a normalized body length where 0 and 1 corresponding to snout and tail tip, respectively: $j_1 - j_5$, from anterior to posterior.

	s_{head} (L)	s_{tail} (L)	$R_{h:t}$	CV
2-segment	0.67±0.06	0.33±0.06	2.14±0.60	0.49±0.17
3-segment	0.54±0.07	0.19±0.05	3.01±1.08	0.56±0.18
4-segment	0.36±0.09	0.17±0.04	2.39±1.12	0.40±0.17
5-segment	0.26±0.06	0.17±0.06	1.80±0.89	0.28±0.13
6-segment	0.18±0.04	0.15±0.05	1.26±0.49	0.18±0.04

Supplementary table 2. Segment configuration of SGM models from two to six segments.

	seg. no.	s_{head} (L)	s_{tail} (L)	$R_{h:t}$	CV
Eel model	5[5,5]†	0.27±0.09†	0.18±0.05	1.70±0.90*	0.27±0.12*
Trout model	3[3,3]	0.55±0.05	0.18±0.05	3.24±1.00	0.60±0.14
Mackerel model	3[3,3]	0.47±0.10	0.20±0.07	2.58±0.95	0.44±0.21
Tuna model	3[3,3]	0.48±0.09	0.18±0.05	2.91±1.24	0.46±0.15

Supplementary table 3. Segment configuration of SGM models' describing four species representative of classical swimming modes. Marker † indicates that the segment configuration variables (segment number and s_{head}) of the eel model was significantly different than the variables of the trout, mackerel, and tuna models ($p < 0.01$). Marker * indicates that the segment configuration variables ($R_{h:t}$ and CV) of the eel model was significantly different than those of the brook trout ($p < 0.05$).

	seg. no.	s_{head} (L)	s_{tail} (L)	$R_{h:t}$	CV
low Re	3[3,4]	0.49±0.14†	0.19±0.06	2.75±1.09*	0.51±0.20†
high Re	4[3,5]	0.37±0.14	0.18±0.06	2.27±1.22	0.37±0.18

Supplementary table 4. Segment configuration of SGM models at low and high Re. Markers † and * indicate significance at $p < 0.01$ and $p < 0.05$, respectively.

	low Re				
	class = 2	**3**	**4**	**5**	**6**
P_{10}	0.462	0.411	0.383	0.290	0.151
P_{25}	0.740	0.603	0.504	0.386	0.191
P_{50}	0.770	0.634	0.475	0.411	0.202
P_{75}	0.521	0.437	0.307	0.291	0.176
P_{90}	0.253	0.226	0.191	0.192	0.117
P_{100}	0.258	0.228	0.181	0.139	0.061
AR_{10}	0.772	0.830	0.961	1.016	0.794
AR_{25}	0.578	0.665	0.768	0.783	0.736
AR_{50}	0.461	0.520	0.571	0.643	0.724
AR_{75}	0.395	0.462	0.485	0.564	0.693
AR_{90}	0.539	0.552	0.486	0.492	0.570
AR_{100}	0.199	0.236	0.285	0.483	0.595
Accuracy (%)	50	91	86	60	86
	high Re				
	class = 2	**3**	**4**	**5**	**6**
P_{10}	0.589	0.462	0.401	0.207	0.178
P_{25}	0.837	0.717	0.579	0.260	0.197
P_{50}	0.891	0.771	0.608	0.271	0.186
P_{75}	0.521	0.442	0.437	0.219	0.145
P_{90}	0.186	0.188	0.243	0.126	0.094
P_{100}	0.212	0.187	0.250	0.113	0.059
AR_{10}	0.568	0.771	1.012	1.020	0.985
AR_{25}	0.464	0.650	0.696	0.841	0.914
AR_{50}	0.312	0.549	0.552	0.720	0.784
AR_{75}	0.332	0.504	0.483	0.580	0.648
AR_{90}	1.356	1.308	0.534	0.564	0.523
AR_{100}	0.330	0.325	0.234	0.406	0.495
Accuracy (%)	67	100	83	82	67

Supplementary table 5. Linear discriminant analysis classifier, class (segment number) means at low and high Re. Predictors (first column) include body perimeter (P) and aspect ratio (AR) at 10%, 25%, 50%, 75%, 90% and 100% SL. The percentage of correctly classified instances (accuracy) are shown at the bottom of each class.

	s_{head}		$R_{h:t}$		CV	
	low Re	**high Re**	**low Re**	**high Re**	**low Re**	**high Re**
intercept	0.550*	0.094	2.166*	0.008	0.577*	-0.047
P_{10}	-2.006*	0.450	-12.937*	4.693	-2.730*	-0.332
P_{25}	1.427*	-0.388	11.099*	-7.943	2.005*	-0.226
P_{50}	-0.080	0.567	-1.953	4.756	-0.491	0.677
P_{75}	-0.269	0.319	-2.401	-22.889	-0.203	1.029
P_{90}	1.073	-2.807*	-5.317	9.474	0.424	-3.543
P_{100}	-0.568	1.244	8.512	0.548	0.566	1.361
AR_{10}	0.083	0.059	0.652	-4.998	0.211	0.124
AR_{25}	0.105	-0.328	1.761	-1.307	0.156	-0.154
AR_{50}	0.331	-0.747	3.978	12.277	0.729	-1.052
AR_{75}	-0.734*	1.590*	-8.912*	-0.685*	-1.683*	1.976*
AR_{90}	0.343*	-0.047	2.358*	-1.373	0.489*	-0.092
AR_{100}	-0.697*	-0.013	-0.154	0.008	-0.380	-0.067
r^2	0.70	0.76	0.40	0.35	0.49	0.43
p	<0.01	<0.01	<0.01	<0.05	<0.01	<0.01

Supplementary table 6. Coefficient of MLR-models at low and high Re. Marker * indicates significance at $p < 0.05$. Input vector (first column) includes body perimeter length (P) and aspect ratio (AR) at 10%, 25%, 50%, 75%, 90% and 100% SL. Predicted outputs were head segment length (s_{head}), length ratio between head and tail segments ($R_{h:t}$) and coefficient of variation between segment lengths (CV). There was no significant relationship between shape parameters and tail segment length (s_{tail}). The coefficient of determination (r^2) and significance level (p) of the MLR-models are also shown at the bottom.

Species	Seg. no.	j_1	j_2	j_3	j_4	j_5
Acipenser brevirostrum	4	0.495	0.765	0.895	-	-
Acipenser brevirostrum	4	0.5	0.715	0.885	-	-
Acipenser brevirostrum	4	0.335	0.59	0.8	-	-
Alosa sapidissima	4	0.365	0.595	0.805	-	-
Alosa sapidissima	4	0.315	0.585	0.805	-	-
Alosa sapidissima	4	0.375	0.64	0.855	-	-
Alosa sapidissima	4	0.36	0.645	0.84	-	-
Anguilla rostrata	5	0.165	0.38	0.575	0.75	-
Anguilla rostrata	5	0.3	0.52	0.72	0.89	-
Anguilla rostrata	6	0.145	0.34	0.53	0.705	0.88
Anguilla rostrata	4	0.37	0.58	0.755	-	-
Anguilla rostrata	6	0.225	0.405	0.565	0.715	0.855
Anguilla rostrata	5	0.245	0.45	0.64	0.81	-
Anguilla rostrata	5	0.36	0.58	0.755	0.9	-
Anguilla rostrata	5	0.19	0.375	0.55	0.73	-
Anguilla rostrata	5	0.305	0.515	0.695	0.86	-
Anguilla rostrata	4	0.395	0.605	0.785	-	-
Archosargus probatocephalus	3	0.61	0.84	-	-	-
Archosargus probatocephalus	4	0.27	0.605	0.815	-	-
Branchiostoma lanceolatum	6	0.185	0.355	0.53	0.7	0.88
Branchiostoma lanceolatum	6	0.175	0.36	0.54	0.71	0.88
Branchiostoma lanceolatum	6	0.13	0.28	0.43	0.59	0.765
Branchiostoma lanceolatum	5	0.18	0.35	0.555	0.75	-
Caranx hippos	2	0.61	-	-	-	-
Caranx hippos	2	0.61	-	-	-	-
Caranx hippos	3	0.58	0.9	-	-	-
Caranx hippos	3	0.575	0.855	-	-	-
Caranx hippos	3	0.6	0.865	-	-	-
Caranx hippos	3	0.555	0.82	-	-	-
Caranx hippos	3	0.54	0.8	-	-	-
Catostomus commersonii	4	0.3	0.61	0.815	-	-
Catostomus commersonii	4	0.225	0.525	0.775	-	-
Catostomus commersonii	4	0.295	0.605	0.825	-	-
Catostomus commersonii	4	0.275	0.595	0.83	-	-
Chaetodipterus faber	3	0.485	0.785	-	-	-
Chitala ornata	4	0.38	0.685	0.89	-	-
Chitala ornata	3	0.605	0.815	-	-	-
Chitala ornata	4	0.425	0.66	0.82	-	-
Danio rerio	5	0.38	0.605	0.755	0.87	-
Decapterus macarellus	2	0.67	-	-	-	-
Decapterus macarellus	3	0.57	0.825	-	-	-
Decapterus macarellus	3	0.585	0.84	-	-	-
Decapterus macarellus	3	0.57	0.8	-	-	-
Decapterus macarellus	3	0.6	0.84	-	-	-
Devario aequipinnatus	4	0.315	0.62	0.88	-	-
Devario aequipinnatus	4	0.285	0.615	0.825	-	-
Devario aequipinnatus	4	0.325	0.62	0.815	-	-
Devario aequipinnatus	4	0.495	0.71	0.895	-	-
Devario aequipinnatus	3	0.39	0.695	-	-	-
Devario aequipinnatus	4	0.39	0.68	0.88	-	-
Eptatretus stoutii	6	0.22	0.385	0.555	0.71	0.84
Esox lucius	5	0.295	0.58	0.755	0.895	-
Esox lucius	5	0.25	0.485	0.685	0.85	-
Esox lucius	5	0.265	0.485	0.68	0.84	-
Haemulon aurolineatum	3	0.615	0.835	-	-	-

Haemulon aurolineatum	3	0.66	0.86	-	-	-
Haemulon aurolineatum	3	0.58	0.805	-	-	-
Haemulon aurolineatum	3	0.59	0.845	-	-	-
Leiostomus xanthurus	3	0.52	0.765	-	-	-
Leiostomus xanthurus	3	0.51	0.775	-	-	-
Leiostomus xanthurus	4	0.43	0.69	0.895	-	-
Lepisosteus platyrhincus	3	0.635	0.85	-	-	-
Lepisosteus platyrhincus	3	0.595	0.825	-	-	-
Lepomis macrochirus	3	0.635	0.865	-	-	-
Lepomis macrochirus	2	0.725	-	-	-	-
Lutjanus griseus	4	0.205	0.635	0.87	-	-
Lutjanus griseus	4	0.23	0.63	0.85	-	-
Lutjanus griseus	4	0.245	0.615	0.84	-	-
Megalops cyprinoides	3	0.555	0.82	-	-	-
Megalops cyprinoides	3	0.54	0.745	-	-	-
Megalops cyprinoides	3	0.495	0.745	-	-	-
Megalops cyprinoides	3	0.47	0.745	-	-	-
Menticirrhus americanus	3	0.535	0.81	-	-	-
Menticirrhus americanus	3	0.52	0.8	-	-	-
Menticirrhus americanus	3	0.4	0.72	-	-	-
Micropterus dolomieu	4	0.345	0.625	0.825	-	-
Micropterus dolomieu	3	0.59	0.84	-	-	-
Micropterus dolomieu	4	0.215	0.505	0.75	-	-
Micropterus salmoides	3	0.675	0.9	-	-	-
Micropterus salmoides	3	0.62	0.825	-	-	-
Mugil cephalus	3	0.5	0.77	-	-	-
Mugil cephalus	3	0.55	0.8	-	-	-
Myxine glutinosa	6	0.145	0.31	0.485	0.65	0.795
Myxine glutinosa	6	0.22	0.42	0.595	0.76	0.9
Myxocyprinus asiaticus	2	0.67	-	-	-	-
Myxocyprinus asiaticus	3	0.64	0.84	-	-	-
Myxocyprinus asiaticus	3	0.62	0.835	-	-	-
Myxocyprinus asiaticus	3	0.55	0.81	-	-	-
Noturus insignis	4	0.51	0.715	0.86	-	-
Noturus insignis	4	0.52	0.73	0.87	-	-
Noturus insignis	4	0.355	0.63	0.805	-	-
Oncorhynchus mykiss	3	0.54	0.805	-	-	-
Oncorhynchus mykiss	3	0.585	0.82	-	-	-
Oncorhynchus mykiss	3	0.58	0.815	-	-	-
Oncorhynchus mykiss	3	0.535	0.78	-	-	-
Perca flavescens	2	0.755	-	-	-	-
Perca flavescens	3	0.655	0.87	-	-	-
Petromyzon marinus	5	0.22	0.43	0.63	0.785	-
Petromyzon marinus	5	0.225	0.465	0.645	0.81	-
Petromyzon marinus	6	0.185	0.38	0.545	0.695	0.82
Pomatomus saltatrix	3	0.54	0.79	-	-	-
Pomatomus saltatrix	3	0.56	0.79	-	-	-
Polypterus senegalus	3	0.58	0.78	-	-	-
Polypterus senegalus	5	0.295	0.48	0.635	0.795	-
Polypterus senegalus	5	0.335	0.535	0.71	0.86	-
Protopterus annectens	4	0.495	0.685	0.805	-	-
Salmo salar	4	0.415	0.665	0.855	-	-
Salmo salar	4	0.335	0.615	0.795	-	-
Salmo trutta	5	0.27	0.52	0.725	0.885	-
Salmo trutta	4	0.28	0.545	0.755	-	-
Salmo trutta	4	0.23	0.53	0.77	-	-

Salvelinus fontinalis	3	0.54	0.81	-	-	-
Salvelinus fontinalis	3	0.55	0.79	-	-	-
Salvelinus fontinalis	3	0.455	0.73	-	-	-
Salvelinus fontinalis	3	0.575	0.815	-	-	-
Salvelinus fontinalis	3	0.63	0.855	-	-	-
Salvelinus fontinalis	3	0.61	0.85	-	-	-
Salvelinus fontinalis	3	0.6	0.84	-	-	-
Salvelinus fontinalis	3	0.54	0.805	-	-	-
Salvelinus fontinalis	4	0.505	0.74	0.9	-	-
Salvelinus fontinalis	3	0.535	0.785	-	-	-
Sander vitreus	4	0.29	0.555	0.81	-	-
Sardinella aurita	3	0.43	0.705	-	-	-
Sardinella aurita	3	0.485	0.75	-	-	-
Scomber scombrus	3	0.59	0.83	-	-	-
Scomber scombrus	3	0.555	0.81	-	-	-
Scomber scombrus	4	0.37	0.675	0.88	-	-
Scomber scombrus	3	0.57	0.83	-	-	-
Scomber scombrus	3	0.41	0.705	-	-	-
Scomber scombrus	3	0.375	0.69	-	-	-
Scomber scombrus	4	0.35	0.66	0.88	-	-
Scomber scombrus	3	0.59	0.85	-	-	-
Scomber scombrus	3	0.52	0.775	-	-	-
Scomber scombrus	3	0.42	0.725	-	-	-
Scyliorhinus retifer	4	0.435	0.655	0.835	-	-
Scyliorhinus retifer	4	0.455	0.67	0.855	-	-
Sphyrna tiburo	4	0.4	0.65	0.82	-	-
Squalus acanthias	4	0.36	0.605	0.795	-	-
Synodus foetens	3	0.455	0.735	-	-	-
Synodus foetens	4	0.44	0.695	0.9	-	-
Synodus foetens	3	0.515	0.775	-	-	-
Thunnus albacares	3	0.595	0.895	-	-	-
Thunnus albacares	3	0.38	0.775	-	-	-
Thunnus albacares	3	0.465	0.845	-	-	-
Thunnus albacares	3	0.385	0.755	-	-	-
Thunnus albacares	3	0.465	0.79	-	-	-
Thunnus albacares	3	0.56	0.82	-	-	-
Thunnus albacares	3	0.48	0.785	-	-	-
Thunnus albacares	3	0.51	0.805	-	-	-
Thunnus albacares	3	0.505	0.885	-	-	-
Thunnus albacares	3	0.49	0.83	-	-	-

Supplementary table 7. Segment number and joint positions of all individuals. The dataset is ordered in alphabetical order.