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Ontogenetic changes in flippers morphometrics in bottlenose dolphins (*Tursiops truncatus*)

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ABSTRACT

The aim of the present study was to investigate and compare the morphometric characteristics of the flippers in male and female bottlenose dolphins (*Tursiops truncatus*) of various ages. We investigated the right flippers of 64 bottlenose dolphinc specimens - 36 males and 28 females, in an age span of from 6 months to 28 years. Two numeric indices were suggested in order to establish the numerical relationship between the external measures of the flipper and the total body length of each animal. The index of the flipper measurements (IxF) directly showed the differences in flipper sizes in the investigated dolphins, whereas the index of the flipper measurements and the total body length (IxBL) displayed the differences in the flipper size in relation to the body length of the studied dolphins. By comparing these indices in dolphins of different ages, noticeable variations in flipper dimensions during total body growth were observed. In bottlenose dolphins, both flipper indices were highly correlated with the animal's body length. The mean value of the index of the flipper measurements and the total body length (IxBL) was somewhat higher in female bottlenose dolphins. Both the flipper indices were highly correlated with the animal's age, and our results suggest that the flipper grows until the tenth year of age, after which it does not change substantially until the 25th year of age. After that age the flipper size starts to decrease.

Key words: bottlenose dolphin, flipper morphology, flipper mobility

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Introduction

The locomotion of marine mammals in water is enabled by the hydrodynamic and fusiform shape of their bodies and by the movements of the posterior part of the body, the tail and caudal fin, which ensure strong body propulsion (WOODWARD et al., 2006). The pectoral fins (flippers) play a role in changing the body position and direction of movement (COOPER et al., 2008) by activating muscles, primarily the m. triceps brachii and the m. deltoideus (COOPER et al., 2007a). Strong activity of these muscles may increase the mineral density of the flipper bones in the dolphin (GUGLIELMINI et al., 2002; LUCIĆ et al., 2010). The flippers are formed by the modification of the pectoral limbs of land mammals; they are flat, and consist of the humerus, the ulna, the radius and the carpal bones and finger phalanges, inserted in connective tissue. This connective tissue fills the space between the finger phalanges, increasing the total surface area of the flipper (COOPER et al., 2007b). The elbow joint and the distal joints of the pectoral limb are not mobile (SEDMERA et al., 1997). Moving is defined by the movements of the shoulder joint, which enables the flipper to act as the stabilizer of the whole body (FISH, 2002). In comparison with land mammals, the size of the autopodium in whales is greater, relative to the total body length, due to hyperphalangy, with the fingers embedded in the common soft tissue that forms the smooth ridged fin (COOPER et al., 2007a). In all whales, the flipper bones are built of spongy bone matter, and compact bone matter is significantly reduced, or completely absent (LUCIĆ et al., 2010). Whales with more flexible bodies and more mobile flippers have a greater ability to change swimming directions and angles rapidly. Whales with less flexible bodies and less mobile flippers manoeuvre more slowly in the water, but attain a higher speed with rectilinear motion (FISH and ROHR, 1999). The speed and ability to quickly change the direction of movement differs depending on environmental conditions and the animal's feeding technique (FISH, 2002; FISH et al., 2007). More flexible, slower and more precise motion, with more pronounced manoeuvring is observed in whales living in habitats with a more complex configuration, as opposed to those living in open seas, and these characteristics of movement develop and improve during life (FISH et al., 2008).

The aim of the present study was to investigate and compare the morphometric characteristics of the flippers in male and female bottlenose dolphins of various ages. This will allow us to discover at what age the dolphin's flipper motion ability develops most intensively, when it is at its peak of development, and whether it deteriorates at a later age. As aging processes affect locomotive organs and the mobility of the body as a whole, these changes are important because they influence the animal's behaviour and its routine activities.

Materials and methods

The right flippers of 64 bottlenose dolphin (*Tursiops truncatus*) specimens - 36 males and 28 females, were investigated, at ages ranging from 6 months to 28 years. All the investigated animals had died in their natural habitat and were found in water or on the shores of the Croatian side of the Adriatic Sea. After a detailed exterior examination of all the carcasses, weighing, measurement of body parameters and necropsy were performed. The age was established using the GLG (Growth Layer Group) method, staining the tooth cross section with Harris's haemalum and counting annual tooth growth zones (MOLINA and OPORTO, 1993). After the physical examination, the following external body parameters were measured, using the method of PERRIN (1975):

TBL - total body length (distance from the tip of the upper jaw to the bottom of the median incisura of the tail fluke).

CrFL - cranial flipper length (distance from the cranial acceptance to the top of the flipper).

CaFL - caudal flipper length (distance from the caudal acceptance to the top of the flipper).

GFW - the greatest flipper width.

In the present investigation, two numeric indices were used in order to establish the numerical relationship between the external measurements of the flipper and the total body length of each animal. One of these indices was named the index of flipper measurements (IxF), and the other, the index of flipper measurements relative to total body length (IxBL). For calculation of these indices, two formulae were developed. The index of flipper measurements includes three main morphometric characteristics of the flipper, which are: cranial flipper length, caudal flipper length, and greatest flipper width. The index of flipper measurements relative to total body length includes three main flipper measurements (the same as the previous index) but in ratio to the total body length.

$$IxF = \frac{CrFL + CaFL}{2} \times GFW$$

$$IxBL = \frac{CrFL + CaFL}{2} \times GFW / TBL$$

All data were analysed using a standard statistics computer program: "Statistica for Windows 9.0". The animals were divided according to sex and classified in the age range from 6 months to 28 years. Correlations were assessed between IxF and IxBL with the morphometric parameters (the body length, the pectoral fin dimensions, the weight and the age of the dolphin).

Results

Flipper and body measurementss in the investigated dolphins. The obtained measurements of the investigated bottlenose dolphins are shown in Table 1.

Table 1. External body measurements and calculated indices of the flippers of Bottlenose dolphins (TBL - total body length; CrFL - cranial flipper length; CaFL - caudal flipper length; GFW - great flipper width; IxF - index of flipper measurements, and IxBL - index of flipper measurements relative to total body length; 1 - males; 2 - females).

Dolphin mark	Age	Sex	Body mass	TBL	CrFL	CaFL	GFW	IxF	IxBL
D 131	3	1	77.0	175	30.0	20.0	10.0	250.0	1.428
D 134	3	1	128.0	223	33.0	22.0	11.0	302.5	1.356
D 136	7	1	161.0	260	39.0	28.0	14.0	469.0	1.803
D 138	7	1	124.0	246	36.0	25.0	12.5	381.2	1.549
D 139	21	1	239.0	294	39.0	28.0	15.0	502.5	1.709
D 140	0.5	2	13.0	117	20.0	14.5	7.0	120.7	1.031
D 141	18	2	197.0	282	42.0	30.0	16.5	594.0	2.106
D 142	23	1	270.0	307	44.0	30.0	18.0	666.0	2.169
D 143	20	2	163.5	263	42.0	31.0	15.5	565.7	2.151
D 149	5	1	186.0	242	36.0	25.0	13.0	396.5	1.638
D 150	4	2	87.0	186	26.0	19.0	9.0	202.5	1.088
D 151	13	2		258	35.0	24.0	14.0	413.0	1.600
D 152	21	2	171.0	262	39.0	28.0	15.0	502.5	1.917
D 156	1	2	71.0	171	28.0	20.0	10.0	240.0	1.403
D 157	6	1	67.0	196	30.0	21.0	11.0	280.5	1.431
D 158	3	1	85.0	191	28.0	19.0	10.0	235.0	1.230
D 159	22	2	298.0	286	41.0	30.0	16.0	568.0	1.986
D 160	0.5	1	14.5	120	18.5	14.0	8.0	129.6	1.080
D 162	26	1	216.0	300	43.0	31.0	16.0	592.0	1.973
D 163	0.5	2	27.5	128	24.0	17.0	9.0	184.5	1.441
D 166	1	1		175	26.0	20.0	9.5	218.5	1.248
D 167	10	2		261	43.0	31.0	14.5	536.5	2.055
D 168	3	1	89.0	199	33.0	24.0	12.0	342.0	1.718
D 169	24	1	314.0	298	48.5	29.0	18.0	697.5	2.340
D 170	17	1	288.0	288	43.0	32.0	17.0	637.5	2.213
D 172	6	1	100.0	227	35.0	24.0	13.0	383.5	1.689
D 173	21	2	169.0	291	40.0	30.0	15.0	525.0	1.804
D 174	1	2	38.0	146	27.0	20.0	9.5	223.2	1.528
D 175	2	2	47.0	162	25.0	18.0	10.0	215.0	1.327

Table 1. (continued)

Dolphin mark	Age	Sex	Body mass	TBL	CrFL	CaFL	GFW	IxF	IxBL
D 177	19	1	234.0	322	47.0	32.0	16.0	632.0	1.962
D 178	12	1	148.0	275	43.0	34.0	15.0	577.5	2.100
D 181	4	2		192	31.0	18.0	11.0	269.5	1.403
D 183	14	2	218.0	267	41.0	30.0	15.5	550.2	2.060
D 184	0.5	1	11.5	118	21.0	15.0	8.0	144.0	1.220
D 186	16	2	204.0	299	42.0	33.0	17.0	637.5	2.132
D 187	0.5	1	22.5	128	23.0	16.0	8.0	156.0	1.218
D 191	2	1	47.5	183	26.0	18.0	7.5	165.0	0.901
D 192	1	2	35.0	132	23.0	16.0	8.0	156.0	1.181
D 193	3	1	79.0	210	26.0	18.0	11.0	242.0	1.152
D 196	26	2	166.0	280	41.0	31.0	15.0	646.0	2.266
D 194	20	1	206.0	285	46.0	30.0	17.0	540.0	1.928
D 198	6	2	117.0	226	35.0	24.0	12.0	354.0	1.566
D 200	28	1	227.0	298	42.0	29.0	16.0	426.0	1.429
D 203	25	2	218.0	280	44.0	35.0	18.0	711.0	2.539
D 203	25	2	218.0	280	44.0	35.0	18.0	711.0	2.539
D 204	4	1	80.0	193	30.0	22.0	9.5	247.0	1.279
D 204	4	1	80.0	193	30.0	22.0	9.5	247.0	1.279
D 205	2	1	72.0	171	25.0	19.0	10.0	220.0	1.286
D 206	5	2	119.0	210	31.0	24.0	11.5	316.2	1.505
D 209	25	2	182.0	287	45.0	31.0	19.0	722.0	2.515
D 211	20	1	232.0	302	51.0	40.0	20.0	864.5	2.862
D 212	20	1	245.0	299	47.0	34.0	18.0	729.0	2.438
D 214	10	1	161.0	250	38.0	29.0	14.0	469.0	1.876
D 215	19	1	304.0	278	42.0	29.0	17.0	603.5	2.170
D 216	3	2	53.0	176	27.0	17.0	9.0	198.0	1.125
D 217	13	2	160.0	281	40.0	30.0	14.5	507.5	1.806
D 219	1	1	50.0	148	24.0	17.0	8.0	164.0	1.108
D 227	4	1	90.0	212	29.0	20.0	10.0	245.0	1.155
D 228	22	1	194.0	274	43.0	31.0	17.0	629.0	2.295
D 231	5	1	137.0	223	33.0	20.0	12.0	318.0	1.426
D 232	26	2	247.0	273	43.0	25.0	15.0	510.0	1.868
D 233	7	1		205	30.0	24.0	11.0	297.0	1.448
D 234	17	2	187.0	284	41.0	31.0	15.0	540.0	1.901
D 235	6	2	117.0	220	33.0	24.0	10.0	285.0	1.295
D 241	25	1	314.0	288	47.0	35.5	18.0	742.5	2.578

Correlation analysis of all the variables in the investigated dolphins. Correlation analysis of all the variables for the dolphins was performed using a basic descriptive statistics method. The variables included: the animal's age, the morphometric parameters (the animal's weight, total body length (TBL), cranial flipper length (CrFL), caudal flipper length (CaFL) and the greatest flipper width (GFW) as well as the calculated indices of flipper measurements, IxF and IxBL.

Table 2. Correlation coefficients between all the variables. All coefficients are statistically significant (TBL - total body length; CrFL - cranial flipper length; CaFL - caudal flipper length; IxF - index of flipper measurements, and IxBL - index of flipper measurements and total body length).

	Age	Body mass	TBL	CrFL	CaFL	GFW	IxF	IxBL
Age	1.00	0.87	0.88	0.89	0.85	0.90	0.89	0.78
Weight	0.87	1.00	0.91	0.91	0.85	0.91	0.89	0.79
TBL	0.88	0.91	1.00	0.96	0.93	0.93	0.92	0.77
CrFL	0.89	0.91	0.96	1.00	0.96	0.96	0.97	0.87
CaFL	0.85	0.85	0.93	0.96	1.00	0.95	0.97	0.88
GFW	0.90	0.91	0.93	0.96	0.95	1.00	0.98	0.92
IxF	0.89	0.89	0.92	0.97	0.97	0.98	1.00	0.92
IxBL	0.78	0.79	0.77	0.87	0.88	0.92	0.92	1.00

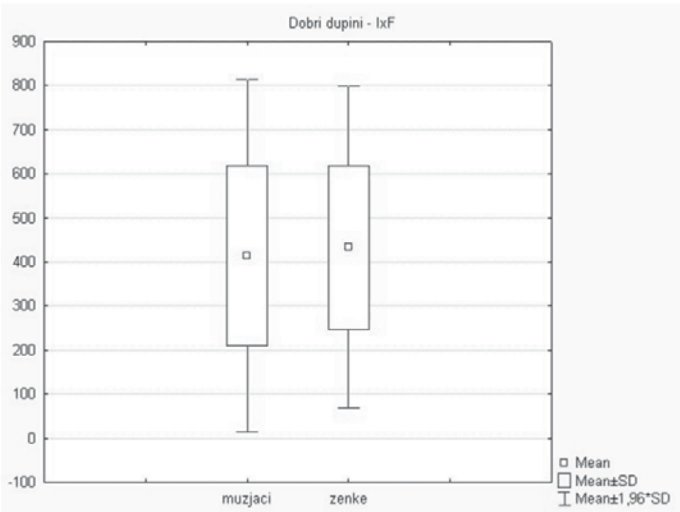

Fig. 1a. Graphical presentation of the variations in mean values of the index of flipper measurements - IxF between male and female animals

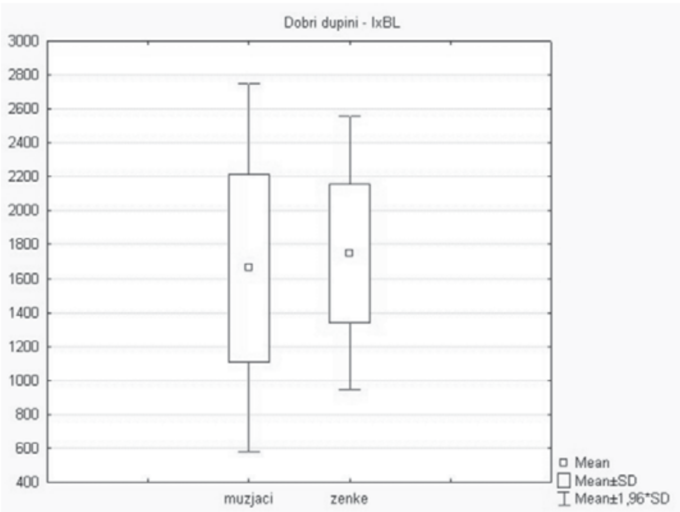

Fig. 1b. Graphical presentation of the variations in mean values of the index of flipper measurements and total body length - IxBL, between male and female animals

The results show that the correlation coefficients between both indices and all the other variables were significant. An exceptionally high correlation (r = 0.98; r = 0.92) was found between IxF and GFW. Both the indices were well correlated with the animal's weight (r = 0.89; r = 0.79), and age (r = 0.89; r = 0.78), as well as TBL (r = 0.92; r = 0.77). The statistical significance of correlations between all variables is shown in Table 2.

The differences between the flipper indices in male and female dolphins. IxF and IxBL were investigated in bottlenose dolphins, between the sexes. In Figure 1a, slight variations of IxF between male and female animals are graphically presented. In Figure 1b, the higher IxBL in the female bottlenose dolphins is noticeable.

The results of the *t*-test showed that the IxF does not differ significantly between males and females ($P<0.2$). The same test showed that the IxBL is significantly different between males and females ($P<0.009$).

Changes to the indices of flipper measurements between the bottlenose dolphins belonging to different age groups. According to the estimated age of the youngest and the oldest animals, the age span of the studied bottlenose dolphins was from 6 months to 28 years.

The results show a high correlation in the index of flipper measurements (IxF) and animal age (r = 0.88) and a somewhat lower correlation in the index of flipper

Table 3. (continued)

measurements and total body length - IxBL) and the dolphin's age (r = 0.77). These correlations are presented in Figs 2a and 2b.

Table 3. Mean values of the index of flipper measurements (IxFM), and index of flipper measurements and total body length (IxBL) according to the estimated age (N - number of animals).

Dolphin age (year)	N	IxF	IxBL
0.5	5	137.57	1137.25
1	5	197.7	1318.16
2	3	200	871.3
3	6	274.3	1376.8
4	4	231.5	1174
5	3	343.56	1523
6	4	325.75	1495.25
7	3	382.4	1600
10	2	502.75	1965.5
12	1	577.5	2100
13	2	460.25	1703
14	1	550.2	2060
16	1	637.5	2132
17	2	588.75	2057
18	1	594	2106
19	2	617.75	2066
20	4	674.8	2429.25
21	3	510	1810
22	2	595.5	2140.5
23	1	666	2169
24	1	697	234
25	3	725	2515
26	3	582.66	1923
28	1	426	1429

The graph in Fig. 3 presents the ascending growth curves for both the investigated flipper indices in the bottlenose dolphins. As Fig. 3 shows, an increase in growth curves for both the indices was noticeable up to the age of 25 years, whereas the values of the studied indices gradually decreased in the oldest animals. An aberration from the ascending growth curve was observed in the dolphins aged 3, 13, 20 and 21 years.

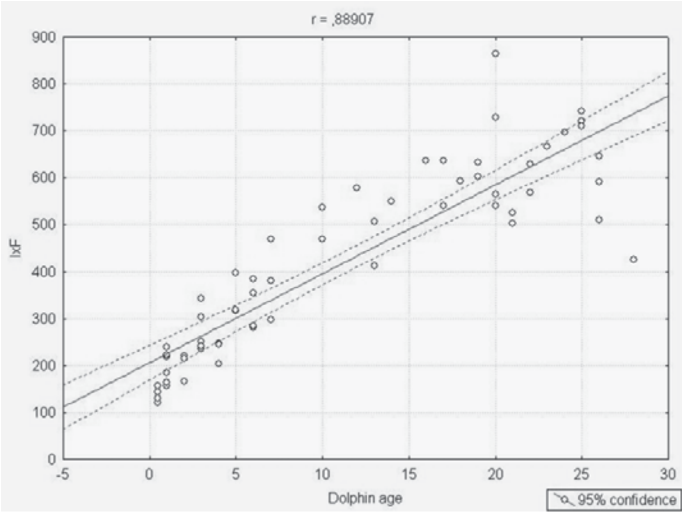

Fig. 2a. Graphical presentation of the correlation in the index of flipper measurements (IxF) and dolphin's age

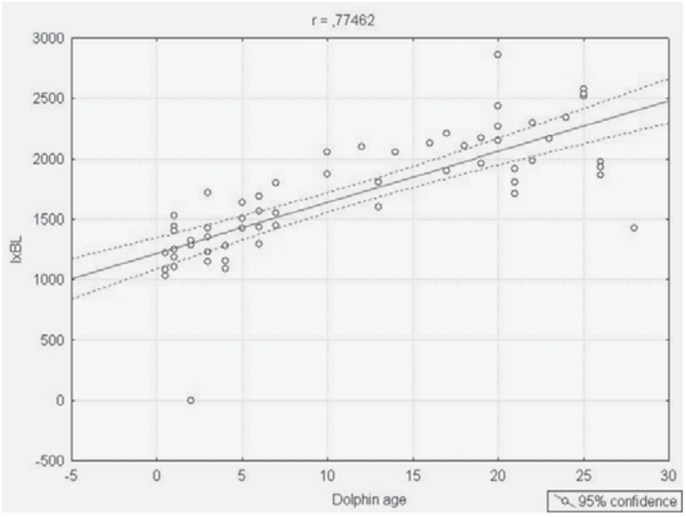

Fig. 2b. Graphical presentation of the correlation in the index of flipper measurements and total body length (IxBL**)** and the dolphin's age

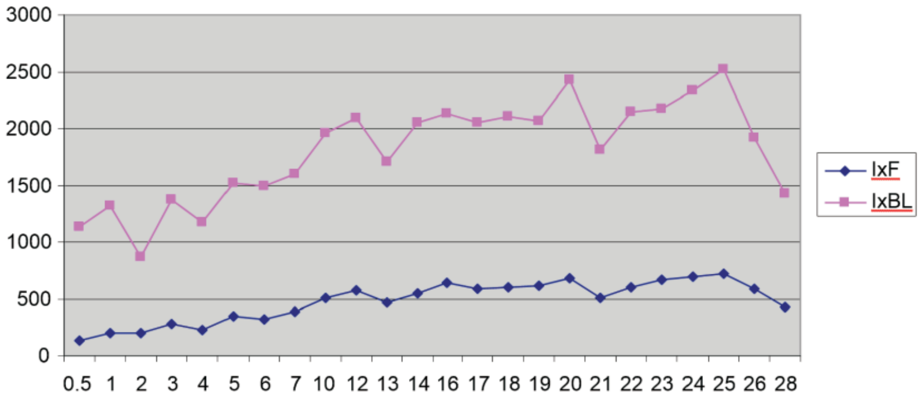

Fig. 3. Growth curves for both the investigated flipper indices according to age in the studied bottlenose dolphins (the index of flipper measurements - IxF**,** the index of flipper measurements and total body length - IxBL**,** and the dolphin's age from 0.5 to 28 years).

Discussion

In the majority of whales, the size of the flippers is in a steady relationship with the total body length (FISH and ROHR, 1999). The cranial and the caudal lengths of the pectoral fins are determined by the length and the shape of the bones forming the fin base. The greatest width of the flipper is defined by the bones embedded in a thick and wide layer of soft tissue, and it is dependent on the variations associated with the technique of flipper use during motion, as well as on the environmental conditions where the dolphin swims and lives. A large and wide flipper, with a well-developed musculature, is characteristic of whales that frequently change their direction of movement. When manoeuvring, dolphins can make abrupt turns, suddenly stop, or move backwards (FISH and ROHR, 1999). The characteristics of the medium in which the animal lives are also important for its motion; for example, the water density and the strength of its currents, its depth, regardless of whether it is sea or fresh water. An example of these influences on fin morphology is the South American river dolphin, with its very broad and very mobile flippers (KLIMA et al., 1980). As all the study animals in the present investigation were from the same habitat, equal environmental conditions were an initial presumption.

The index of flipper measurements (IxF) directly showed the differences in the flipper size in the investigated dolphins, whereas the index of flipper measurements and total body length (IxBL) displayed the differences in flipper size in relation to the body length of the dolphins. By comparing these indices in dolphins of different ages, clearly noticeable variations of flipper dimensions during total body growth were observed. In bottlenose dolphins, both flipper indices were highly correlated with the animal's size, i.e., with its body length and weight. A particularly high correlation was seen in IxF, which showed that the size of the flipper accompanies the animal's growth. The analysis of the values of the indices of flipper measurements in bottlenose dolphins in relation to sex, displayed very low mean differences in both the indices between males and females. The mean value of IxBL was somewhat higher in the female bottlenose dolphin study group. In the Adriatic Sea, bottlenose dolphins live in small groups, although solitary animals are not uncommon. The latter frequently approach the shore, and hunt in underwater areas with a diversified seabed configuration. A slight increase in IxBL in the females suggests a somewhat more developed flipper than in male dolphins. This might be associated with the more intensive use of the flippers in swimming while approaching the shore more frequently, or during calf care.

Both the flipper indices (IxF and IxBL) are highly correlated with the animal's age. The graphic presentations of the ascending growth curves of these indices (Fig. 3) suggest that the flipper grows until the tenth year of age, after which it does not change substantially until the 25^{th} year of age. After that year, the flipper size starts to decrease. The dolphin probably develops its manoeuvring ability in the course of its life, and this is accompanied by alterations in the flipper morphology. During the most active period of its life the dolphin's flipper does not change essentially, but in older animals it gradually decreases, together with an overall reduction in life activities. The more intensive aberrations in growth curves at the ages of 3, 13, 20 and 21 years were probably associated with possible incorrect estimates of the dolphin's age or with individual variations.

The present study has proposed indices that could serve as indicators of manoeuvring ability in relation to age or sex in individual species of dolphins. It was observed that the size of the dolphin's flippers changes during the animal's life. This ability gradually develops in young animals, achieves a certain level that is maintained during the animal's most active period and, finally, gradually decreases in older animals. In the future, it would be interesting to investigate similar parameters in other kinds of whales. Particularly interesting is the presumption of possible differences within different populations of bottlenose dolphins that live in different environmental conditions.

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SAŽETAK

Cilj ovog istraživanja bio je usporedba morfometrijskih obilježja prsne peraje u mužjaka i ženki dobrih dupina različite dobi. Istražene su desne prsne peraje od 64 dobra dupina (*Tursiops truncatus*) - 36 mužjaka i 28 ženki u dobnom rasponu od 6 mjeseci do 28 godina. Predložena su dva numerička indeksa kojima bi se utvrdila numerička povezanost između vanjskih mjera prsne peraje i ukupne dužine tijela svake životinje. Indeks mjera prsne peraje (IxF) izravno pokazuje razlike u veličini prsne peraje istraženih dupina, dok indeks mjera prsne peraje i ukupne dužine tijela (IxBL) pokazuje razlike u veličini prsne peraje u odnosu na ukupnu dužinu tijela istraženih dupina. Usporedbom tih indeksa u dupina različite dobi utvrđene su varijacije u dimenzijama prsne peraje tijekom ukupnog rasta tijela životinje. U dobrih dupina, oba indeksa bila su u visokoj korelaciji s ukupnom dužinom tijela. Srednja vrijednost indeksa mjera prsne peraje i ukupne dužine tijela bila je nešto veća u skupini ženki istraženih dupina. Oba indeksa bila su u visokoj korelaciji s dobi životinje te naše istraživanje pokazuje da prsna peraja u dupina raste do dobi od 10 godina, nakon čega se značajno ne mijenja do dobi od 25 godina. Nakon te dobi, veličina prsne peraje počinje se smanjivati.

Ključne riječi: dobri dupin, morfologija prsne peraje, pokretljivost prsne peraje