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Research Article

Growth Patterns and Body Condition of Notothenioid Fish (Genus *Trematomus*) From the Antarctic Peninsula and Weddell Sea

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Growth patterns and body condition of 10 species of *Trematomus* (family Nototheniidae) collected off the Antarctic Peninsula and in the Weddell Sea during seven cruises carried out between 2002 and 2022 were estimated by length–weight relationships (LWRs) and relative condition factors (K_{rel}). Most of the investigated species exhibited positive allometric growth, except for males of *T. scotti* and females of *T. tokarevi*, which showed isometric growth. Sex-related differences of slope (b) in the LWRs were recorded only in *T. eulepidotus* and *T. scotti*. No slope differences were found when comparing populations from the two sampling areas. The form factor, derived from the LWR parameters, was a reliable indicator of body shape and was consistent with the mode of life of each species. K_{rel} was evenly distributed around unity, although data dispersion differed among the species. The overall similarity of growth patterns and body condition among the different species of *Trematomus* was likely due to their genetic similarity and common life history strategies despite their wide spatial distributions and different modes of life.

Keywords: Antarctic fish; condition factor; length–weight relationships

1. Introduction

The continental shelf surrounding the Antarctic continent and the sub-Antarctic islands hosts a unique group of fishes, the Notothenioidei, which includes 110 species of a striking adaptive radiation dating to the early Miocene [1]. Derived from a common benthic ancestor, this group progressively colonized all available marine biotopes, from pelagic to benthic habitats and from inshore to upper slope waters [2]. Within the family Nototheniidae, the genus *Trematomus* is the most speciose clade, consisting of 15 species whose phylogenetic relationships have been recently resolved [3]. They are typical of the high-Antarctic shelf waters, exhibiting demersal (*T. bernacchii*, *T. hansoni*, *T. newnesi*, *T. nicolai*, *T. pennellii*, *T. scotti*, *T. tokarevi*, and *T. vicarius*), epibenthic (*T. eulepidotus*, *T. lepidorhinus*, and *T. loennbergii*), benthopelagic (*T. amphitreta* and *T. peninsulae*), and cryopelagic (*T. borchgrevinki* and *T. brachysoma*) modes of life [4–7]. Except for *T. amphitreta*, *T. peninsulae*, and *T. vicarius*, which are recorded only from McMurdo Sound, Palmer Archipelago and South Georgia, respectively, all other species have a circum-Antarctic distribution [8].

Establishing the length–weight relationships (LWRs) is one of the most common tools used in fisheries management to provide information on growth patterns and nutritional condition of fishes, allowing assessment of the weight of fish from size frequency and thus biomass [9]. The LWR in fishes generally follows the cube law, volume increases as the cube of linear dimensions, in cases of isometric growth patterns [10]. However, the LWR parameters differ significantly among species in relation to their body shape, as well as within the same species based on the condition of individual

Table 1: Length–weight relationships of *Trematomus* spp. from the Antarctic Peninsula (AP) and Weddell Sea (WS).

Species	Site	Sex	*n*	TL (cm)	TW (g)	*a*	*b*	r^2	Growth	Significance	*F*-test
Trematomus bernacchii	AP	♂	14	18.5–33.5	68–653	0.0012	3.76	0.98	+	**	ns
	AP	♀	20	17.5–39.5	64–1171	0.0020	3.63	0.99	+	**	
Trematomus eulepidotus	AP	♂	241	8.5–28.5	5–350	0.0012	3.73	0.98	+	**	*
	AP	♀	371	8.5–36.5	4–730	0.0015	3.64	0.99	+	**	
	WS	♂	115	11.5–30.0	12–322	0.0016	3.62	0.98	+	**	*
	WS	♀	164	13.5–35.0	26–842	0.0014	3.76	0.98	+	**	
Trematomus hansoni	AP	♂	9	10.5–31.5	11–441	0.0033	3.39	0.98	+	*	ns
	AP	♀	46	11.5–43.5	13–1249	0.0023	3.50	0.99	+	**	
Trematomus lepidorhinus	WS	♂	11	12.5–19.5	15–71	0.0013	3.64	0.97	+	**	ns
	WS	♀	19	12.0–24.5	13–154	0.0022	3.45	0.98	+	**	
Trematomus loennbergii	WS	♂	38	14–26	17–184	0.0009	3.75	0.96	+	**	ns
	WS	♀	67	14.5–31	23–393	0.0008	3.77	0.96	+	**	
Trematomus newnesi	AP	♂	32	13.0–26.5	20–298	0.0017	3.66	0.98	+	**	ns
	AP	♀	48	14.5–25.5	20–198	0.0009	3.84	0.95	+	**	
Trematomus nicolai	AP	♀	7	15.5–33.5	39–590	0.0021	3.57	0.99	+	**	
Trematomus pennellii	WS	♂	5	8.1–21.0	5.7–139	0.0018	3.66	0.98	+	*	ns
	WS	♀	7	8.1–27.0	5.7–345	0.0012	3.81	0.99	+	**	
Trematomus scotti	AP	♂	23	10.5–19.0	10–51	0.0095	2.93	0.95	=	**	**
	AP	♀	31	11.5–20.0	10–107	0.0021	3.56	0.94	+	**	
	WS	♂	71	7.5–15.0	3.0–28	0.0065	3.06	0.91	=	**	**
	WS	♀	100	7.5–17.0	2.8–45.0	0.0024	3.49	0.93	+	**	
Trematomus tokarevi	WS	♀	5	13.5–18.5	37–112	0.0084	3.22	0.97	=	**	

Note: n = number of specimens; a = intercept, b = slope, and r^2 = coefficient of determination of the linear regression; + = positive allometry; = isometry; ns = not significant ($p > 0.05$).
Abbreviations: TL = total length, TW = total weight.
*Significant ($p < 0.05$).
**Highly significant ($p < 0.01$).

fish [11]. Derived from the LWR, condition factors are widely used to evaluate the well-being or fitness of fish populations and reflect seasonal fluctuations of metabolism, patterns of gonad maturation, and food intake [12].

Despite a number of studies dealing with the LWRs and condition factors of species from different marine and freshwater environments [13], few data have been published on notothenioid fishes. Fernández et al. [14] reported LWRs in six notothenioid species from sub-Antarctic waters (Beagle Channel, Argentina), whereas Wei et al. [15] provided LWRs of five species associated with the krill fishery in the Atlantic sector of the Southern Ocean. In addition, Kim et al. [16] analyzed both LWRs and condition factors of six notothenioids collected off King George Island (South Shetlands) and off Terra Nova Bay (Ross Sea).

In this context, the genus *Trematomus* is one of the most interesting notothenioid lineages from a comparative point of view, consisting of a number of species with a wide ranging distributions and different lifestyles linked to body morphology [17]. In the present study, we compared the LWRs and condition factors of 10 species of *Trematomus* collected off the Antarctic Peninsula and in the Weddell Sea.

2. Materials and Methods

Fish samples were collected in summer aboard the RV *Polarstern* during the Antarctic cruises PS61 (2002), PS69 (2006), PS79 (2012), and PS112 (2018) off the tip of the Antarctic Peninsula and PS82 (2014), PS96 (2015), and PS129 (2022) in the south-western Weddell Sea. Fishing operations were carried out using a commercial-sized bottom trawl and an Agassiz trawl hauled over a wide depth range (50–1750 m). After sorting, fishes were measured from the tip of the mouth to the end of the caudal fin (total length [TL]) to the nearest half cm below and weighed in grams (total weight [TW]). Sex was macroscopically evaluated based on gross gonad appearance.

The LWR was separately assessed for each species, sampling site and sex using the formula $TW = aTL^b$, where TW is the total weight in g, TL is the total length in cm, and a and b are the function parameters [10]. A simple linear regression was applied to the linearized form of the above function as $\log TW = \log a + b \log TL$, where $\log a$ is the intercept and b is the slope of the regression, and the least squares method was used for parameter estimation. The coefficient of determination (r^2) was used to assess the goodness of fit of the regression model of the LWR. The slope indicates isometric growth in body proportion if $b \sim 3$, whereas it indicates positive or negative allometry if $b > 3$ or $b < 3$, respectively [9]. Departure from isometric growth (i.e., $b \neq 3$) was evaluated by applying a t-test to the equation $t = (b - 3)\ SE^{-1}$, where SE is the standard error of b. Finally, an F-test was used to compare the parameter b between sexes of the same species and within sexes of the same species from different sampling sites [18]. A linear regression was applied to the parameters b and $\log a$ of all species plotted together, and the slope (S) obtained was used to estimate the form factor by the equation $a_3 = 10^{\log a - S(b-3)}$, which can be used to infer the body shape of the species and to compare them to each other [10].

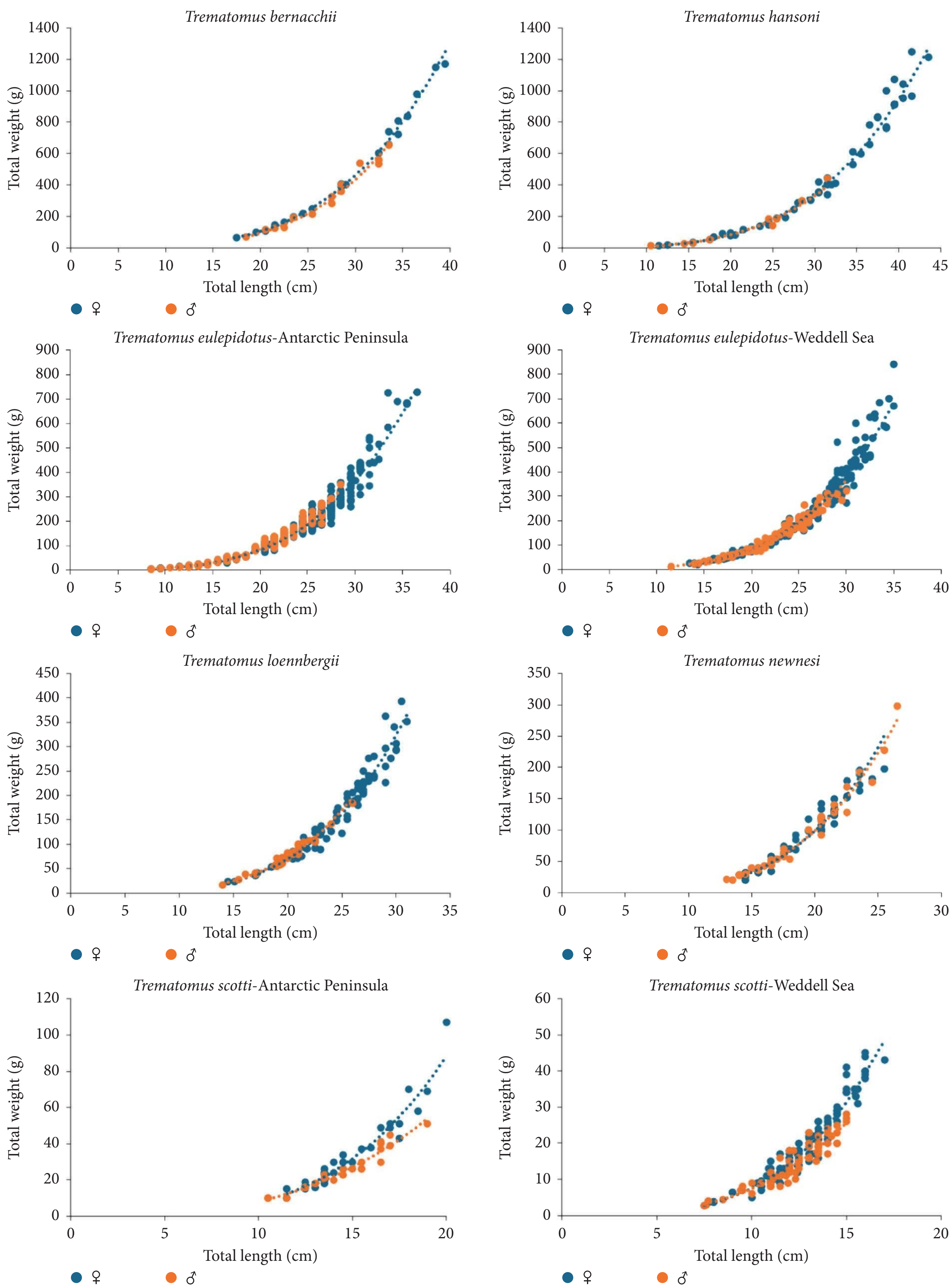

Figure 1: Scatter plots showing the length–weight relationships (LWRs) assessed for the most abundant species of *Trematomus*.

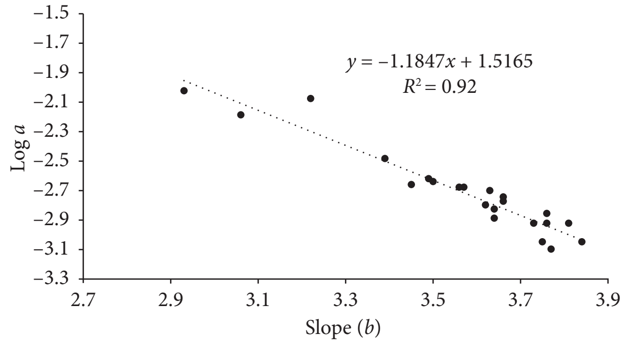

FIGURE 2: Scatter plot showing the relationship between the LWR parameters estimated for the *Trematomus* spp.

Following the recommendation of Bolger and Connolly [12], we used both parameters *a* (calculated as the antilogarithm value of log *a*) and *b* to calculate the relative condition factor (K_{rel}) [19] in the form $K_{rel} = \text{TW}\ (aTL^b)^{-1}$, where TW is the total weight in g and TL is the total length in cm. K_{rel} compares the observed weight of an individual with the mean weight for that length estimated by the LWR [9]. It assumes values > 1 or < 1 in case of good or poor overall condition than the average, respectively. The nonparametric Mann–Whitney pairwise test was used to test intraspecific sex-related and interspecific variations of K_{rel}. All statistical analyses were performed using the Paleontological Statistics (PAST) software package [20].

3. Results

Growth pattern and body condition were estimated for 10 species of *Trematomus*. The LWRs were calculated for each sex and then compared within each species and between populations of the same species living in different areas (i.e., Antarctic Peninsula and Weddell Sea) (Table 1). All the investigated species exhibited positive allometric growth patterns (Figure 1), except for *T. tokarevi* and males of *T. scotti*, which showed isometric growth (Table 1). The slopes (parameter b) of LWRs were generally not significantly different between sexes, except for *T. eulepidotus* and *T. scotti*. Both sexes of *T. eulepidotus* showed allometric growth, but the slopes were significantly higher in males than in females off the Antarctic Peninsula, but the opposite in the Weddell Sea. Females and males of *T. scotti* were characterized by positive allometric and isometric growth, respectively, with females showing consistently higher slopes than males in both areas (Table 1). Finally, comparing the populations of *T. eulepidotus* and *T. scotti* collected in the two areas, no statistical difference was found within sexes. Pooling data from all the species investigated, the LWR parameters log *a* and *b* were inversely related (Figure 2). The form factor calculated for each species was plotted to explore the relationship between body shape and lifestyle and indicated a high consistency between them (Figure 3).

K_{rel} was first calculated for each sex and site and then compared with each other. As no statistical difference was found between them in all comparisons (Mann–Whitney pairwise test, $p > 0.05$), K_{rel} was calculated for each species and site by combining all values (Figure 4). Although the range of K_{rel} values differed considerably among the species, each paired comparison was not statistically significant (Mann–Whitney pairwise test, $p > 0.05$ for all comparisons).

4. Discussion

Based on the LWRs estimated in this study, the species of *Trematomus* shared a positive allometric growth pattern, indicating an increase in relative body thickness during ontogeny [10]. This is a common feature observed in several notothenioid fishes living either in high-Antarctic (e.g., [15, 16, 21–23]) or in sub-Antarctic waters [14]. Compared with previous studies, slopes of LWRs calculated for males and females of *T. bernacchii* (3.51 and 3.95) and *T. newnesi* (3.66 and 3.25) off the Danco Coast [24] were similar to our estimates, although with an inverse relationship between sexes. On the other hand, LWR slopes estimated for males and females of *T. lepidorhinus* (3.29 and 3.15) and *T. pennellii* (3.27 and 3.29) from the Weddell Sea [22] were remarkably lower than our estimates, likely due to the different size ranges between the two studies [25]. Finally, LWR slopes recorded for males and females of *T. eulepidotus* (3.16 and 3.26) and *T. scotti* (3.01 and 3.31) from the Weddell Sea were lower than and comparable with our values, respectively. Summarizing our results, growth patterns derived from the LWRs are species specific, with low variability across their areas of distribution and between sexes, likely due to intrinsic physiological factors. In addition, the form factors derived from the LWR parameters proved to be a reliable indicator of the body shape, which in turn was used to infer the different modes of life for *Trematomus* spp. [26].

K_{rel} calculated for each species were evenly distributed around unity, although in some species, the individual variability was higher, such as *T. eulepidotus*, *T. newnesi*, and *T. scotti*. Nevertheless, K_{rel} did not differ significantly at intra- and interspecific levels, or geographically. For instance, the mean values of K_{rel} for *T. bernacchii* and *T. newnesi* estimated in the present study from the Antarctic

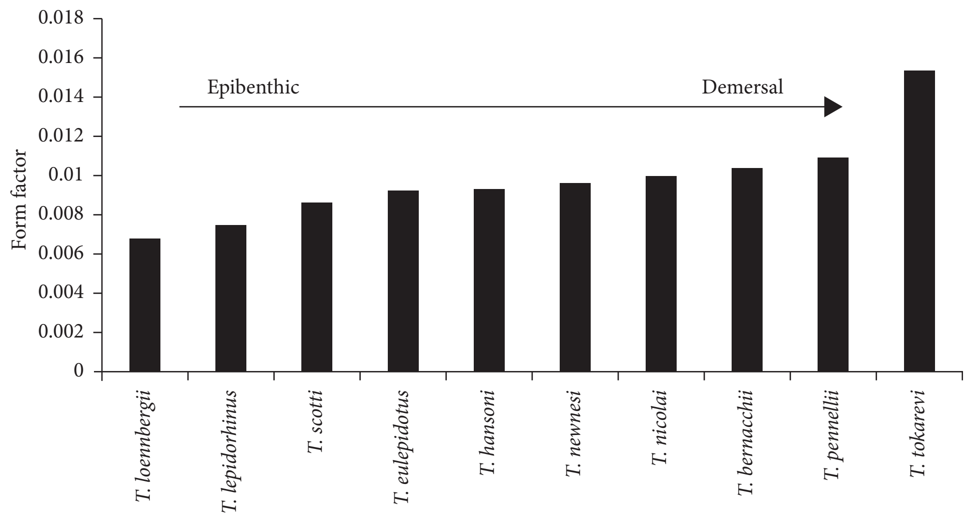

FIGURE 3: Bar plot with the form factor calculated for each species of *Trematomus* in relation to their mode of life.

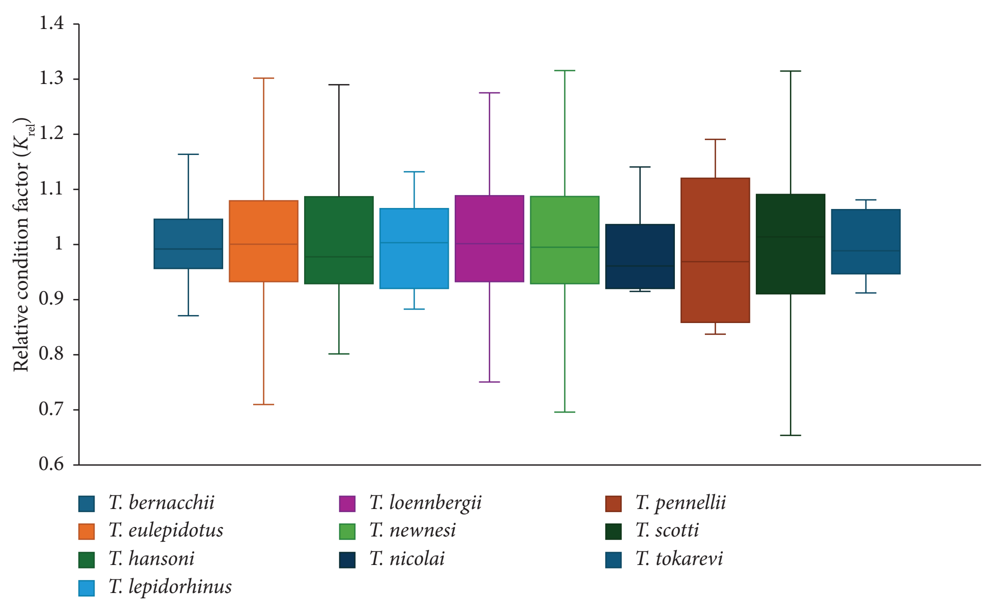

FIGURE 4: Box plots showing the relative condition factor (K_{rel}) evaluated for all the species of *Trematomus* investigated.

Peninsula were the same as those reported in the Ross Sea [16].

In conclusion, despite the variable environmental factors encountered in their wide spatial distribution and during their different modes of life, *Trematomus* species exhibited similar growth patterns and body conditions. This is likely as a consequence of their shared ancestry.

Data Availability Statement

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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