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Research Article

Allometric growth during the early development of the long-snout seahorse *Hippocampus reidi* Ginsburg, 1933

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ABSTRACT. The long-snout seahorse (*Hippocampus reidi*) is one of the most traded seahorse species globally. While information is available regarding the rearing and growth of this species, there has been no clear description of the morphological changes that occur during early development. In this study, we describe the allometric growth patterns during the first 30 days of development of *H. reidi* under culture conditions at the commercial farm "INGENS, Cultivos Marinos" in Mazatlán, Mexico. Juveniles were bred from captive broodstock, and three individuals were sampled daily. The wet weight was recorded, and digital photographs were taken of each individual. Eleven body segments were measured in each juvenile, and the allometric growth was assessed using the potential model. Three developmental stages were identified based on growth rate, and different body proportions and growth coefficients were detected in each stage. Our findings emphasize the significance of snout and tail growth in younger seahorses (stage I, standard-length (SL) interval = 6.4-12.1 mm). Most of the inflection points of the growth coefficients of the body segments occurred within a narrow SL interval (2 mm) at the end of stage I, indicating a change in growth rates and body shape that prepares the young seahorse for stage II. Stage II (SL interval: 12.2-17.51 mm) is characterized by significant ecological traits of this species, including reduced swimming activity, substrate attachment, and ambush feeding. Stage III was observed from an SL of 17.6 mm onwards. Our results could have significant implications for the species' rearing protocols.

Keywords: *Hippocampus reidi*; long-snouted seahorse; early development; growth patterns; allometric growth

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INTRODUCTION

The long-snout seahorse *Hippocampus reidi* Ginsburg, 1933, is one of the four species of seahorses distributed in Mexico. It can be found in the coastal waters of the western Atlantic, from North Carolina (USA) to southern Brazil. The adults can reach a height of 18 cm. It has 31-39 tail rings and 11 trunk rings. It has 17 dorsal rays and 16 pectoral fin rays. Typically found at 15-55 m depth. Seagrass, macroalgae, or corals are preferred substrates (Lourie et al. 2004).

The long-snout seahorse is among the most traded species in international markets, partly due to its vibrant colorations, including red, orange, brown, and yellow (Koldewey & Martin-Smith 2010). It also plays a significant role in traditional Asian medicine and the ornamental trade (Kumaravel et al. 2012, Zhang et al. 2017). Additionally, anthropogenic impacts, primarily bycatch, and deterioration of their distribution areas are significant factors affecting wild populations (Vincent et al. 2011). Therefore, *H. reidi* is classified as Near Threatened (NT) by the International Union for Conser-

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vation of Nature and Natural Resources, and its population trend is considered decreasing (Foster & Vincent 2004). It is protected under Mexican law through the NOM-059-SEMARNAT as a species subject to special protection.

Given these conservation concerns, captive breeding has emerged as a viable strategy to alleviate pressure on wild populations while satisfying the increasing market demands (Hora & Joyeux 2009). In this sense, research has been conducted on various aspects of *H. reidi* culture, including its feeding and growth (Willadino et al. 2012, Pham & Lin 2013, Randazzo et al. 2018), reproduction (Olivotto et al. 2008, Hora & Joyeux 2009), and development (Novelli et al. 2015, 2018).

However, a gap exists in our understanding of the allometric growth patterns during the early stages of development of *H. reidi*, which could provide insights into the low survival rates observed in juvenile seahorses in captivity. Allometric growth refers to the differential growth rates of various body parts (Gould 1966), which can have significant implications for a species' ecological and biological functions.

Previous studies on other fish species have demonstrated the presence of allometric growth patterns during early development (Peña & Dumas 2009, Saemi-Komsari et al. 2018, Kupren et al. 2019, Peña et al. 2023). In the case of seahorses, similar allometric growth patterns have been documented in various species, including the spotted seahorse *Hippocampus kuda* Bleeker, 1852 (Choo & Liew 2006) and the Pacific seahorse *H. ingens* Girard, 1858 (Peña & Zúñiga-Villarreal 2023). These studies highlighted the significance of the seahorse's early development stages, during which crucial transitional events occur with major ecological implications, such as the transition from a pelagic to a benthic lifestyle and a concomitant shift in feeding mechanism, which suggests that these patterns may also be critical for *H. reidi*.

The description of allometric growth patterns during development provides a better understanding of the changes in the body until the final body form is achieved, which has been suggested to occur around 30-40 days of age, as reported for *Hippocampus guttulatus* Cuvier, 1829 (Ofelio et al. 2018). Therefore, the primary goal of the current study was to investigate the allometric growth patterns of *H. reidi* during the first 30 days of development. By elucidating these patterns, the research aims to enhance our understanding of the morphological changes occurring during this crucial period. This information could inform improvements in rearing techniques and feeding practices, ultimately contributing to the successful culture of this species in captivity for both commercial and conservation purposes. Understanding these growth dynamics is not just vital for aquaculture but also for broader ecological insights related to the species' survival and adaptation in changing environments.

MATERIALS AND METHODS

Following the principles of good laboratory animal care, the procedures of animal manipulation and sampling reported in the present study were conducted according to the Official Mexican Standard NOM-033-SAG/ZOO-2014 "Methods for killing domestic and wild animals".

The juveniles for this study were obtained from a single spawn of *H. reidi* broodstock maintained in captivity at "INGENS, Cultivos Marinos" in Mazatlan, Mexico. The juveniles were cultivated in 100 L tanks at 24-27°C, with a salinity of 33-37, an O_2 concentration of >5 mg L^{-1}, and a photoperiod of 12:12 (light:dark), with slight aeration. They were fed *ad libitum* with *Artemia* nauplii and metanauplii twice a day (at 09:00 and 14:00 h). Every day, starting on day 1 and until day 30, three juveniles were haphazardly sampled and euthanized with a 4% phenoxyethanol solution, rinsed with tap water, fixed in a paraformaldehyde solution (4%), and stored in Eppendorf tubes.

The wet weight of every juvenile was recorded using a digital balance (precision 0.0001 mg) and photographed with a digital camera (Sony A6000). Ten body segments and the standard length (SL) were measured to the nearest 0.001 mm in every photograph using photo image analysis software (ImageJ v.2) (Peña & Zúñiga-Villarreal 2023). Each measurement was according to Lourie (2003) (Fig. 1).

The presence of different developmental stages was revealed by the occurrence of inflection points detected in the growth curve of age (*x*) and SL (y). An inflection point is the SL at which the growth coefficient (*b*) changes direction significantly. The inflection points were initially visually inferred in the growth curve at the SL, where the curve changed direction. Then, a linear regression model ($y = a + bx$, where a is the intercept and b is the growth coefficient) was applied to obtain the growth coefficient for each developmental stage before and after the inflection point. A *t*-test was then used to evaluate whether the two slopes differed significantly. Additionally, the length-weight relationship was evaluated using the power function.

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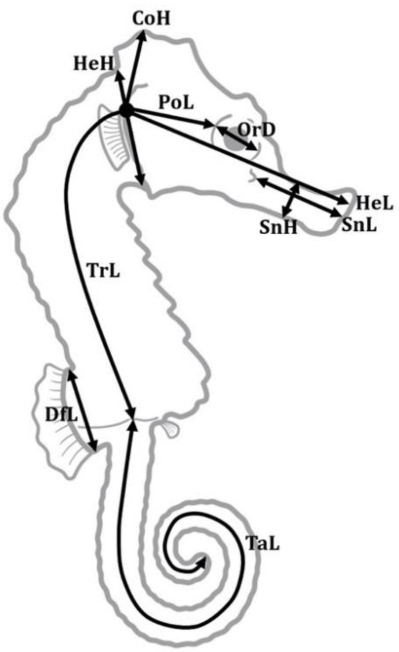

Figure 1. Measured body segments in juvenile long-snout seahorse *Hippocampus reidi*. In the cephalic region: the head length (HeL), the distance from the tip of the snout to the mid-point of the cleithral ring; the coronet height (CoH), the diagonal distance from the mid-point of the cleithral ring to the median groove of the coronet; the snout length (SnL), from the tip of the snout to the anterior side of orbit (eye socket); the snout height (SnH), the distance between the dorsal and the ventral surfaces at the middle point of the snout; the orbital diameter (OrD), between the anterior and posterior inside edges of the orbit; the postorbital length (PoL), from the posterior edge of the orbit to the mid-point of the cleithral ring; and the head height (HeH), from the point behind the coronet to the point behind the cheek spine. In the trunk region: the trunk length (TrL), the curved distance from the mid-point of the cleithral ring to the mid-point of the last trunk ring; and the dorsal fin length (DfL), the distance between the anterior and posterior insertion points of the fin rays. The tail length (TaL) is the distance from the mid-point of the last ring in the trunk to the tip of the tail. The standard length (SL) was defined as the sum of HeL, TrL, and TaL (Lourie 2003).

The allometric growth for each measured body segment in every developmental stage was estimated using the power function: $y = ax^b$, where SL is the independent variable (x), the body segment is the dependent variable (y), and b indicates the growth coefficient, when $b = 1$, an isometric growth is present, but if $b < 1$ or $b > 1$, a negative or a positive allometric growth is observed, respectively (Fuiman 1983). In addition, a *t*-test was applied to confirm if the *b*-value differed significantly from the isometric growth value ($b = 1$). Furthermore, the presence of inflection points during the growth of each body segment was calculated by comparing the slopes of linear regressions from X_{min} to $X_{intermediate}$ and from $X_{intermediate}$ to X_{max} using a *t*-test to evaluate if the two slopes differed significantly. $X_{intermediate}$ was defined as a value that ranged iteratively from $X_{min} + 2$ to $X_{max} - 2$ according to Peña et al. (2023).

RESULTS

The newly hatched juveniles of *H. reidi* exhibited a seahorse-like body form, although several body proportions differed from those of the adults. Nevertheless, the main meristic characters of the species were also present from birth, namely, 16 pectoral fin rays and 11 dorsal fin rays. The 11 rings in the trunk and the 39 rings in the tail were also present. The main color of the juveniles was dark brown. The SL and wet weight of *H. reidi* at day 1 were 6.83 ± 0.52 mm (mean ± standard deviation) and 1.133 ± 0.0003 mg, respectively. At the end of the studied period, the maximum SL and wet weight reached by the juveniles were 23.74 ± 3.12 mm and 55.0 ± 0.0036 mg, respectively. The *b*-value (2.91 ± 0.088) of the length-weight relationship was not significantly different from the theoretical value of isometric growth ($t_{87} = -1.02$, $P = 0.31$) (Fig. 2a), indicating isometric growth.

Three developmental stages were detected in the SL growth curve. Each stage showed a different growth rate. The first stage occurred from day 1 (SL = 6.4 mm) until day 6 (SL = 12.1 mm) with a growth rate of 0.89 mm d^{-1} ($y = 5.818 + 0.891x$, $R^2 = 0.91$; degrees of freedom, d.f. = 1, F = 53.38, $P = 0.0007$). The second stage was observed from day 7 (SL = 12.2) until day 22 (SL = 17.51 mm) with a growth rate of 0.30 mm d^{-1} ($y = 9.981 + 0.305x$, $R^2 = 0.74$; d.f. = 1, F = 32.07, $P = 0.00006$); and stage III occurred from day 23 (SL = 17.6 mm) and onwards with a growth rate 1.03 mm d^{-1} ($y = (-7.81) + 1.03x$, $R^2 = 0.67$; d.f. = 1, F = 10.17, $P = 0.024$) (Fig. 2b).

The measured body segments exhibited different allometric growth patterns across the three developmental stages. In the first stage, only the tail length (TaL) and snout length (SnL) showed positive allometry with growth coefficients of $b = 1.13$ and $b = 1.65$, respectively. The head length (HeL) showed an isometric growth ($b = 0.95$), and all the other body segments showed a negative allometric growth (Table I). In the second stage, the growth of TaL ($b = 1.12$) and head height (HeH) ($b = 1.10$) was positively allometric. Other body segments, such as trunk length (TrL), coro-

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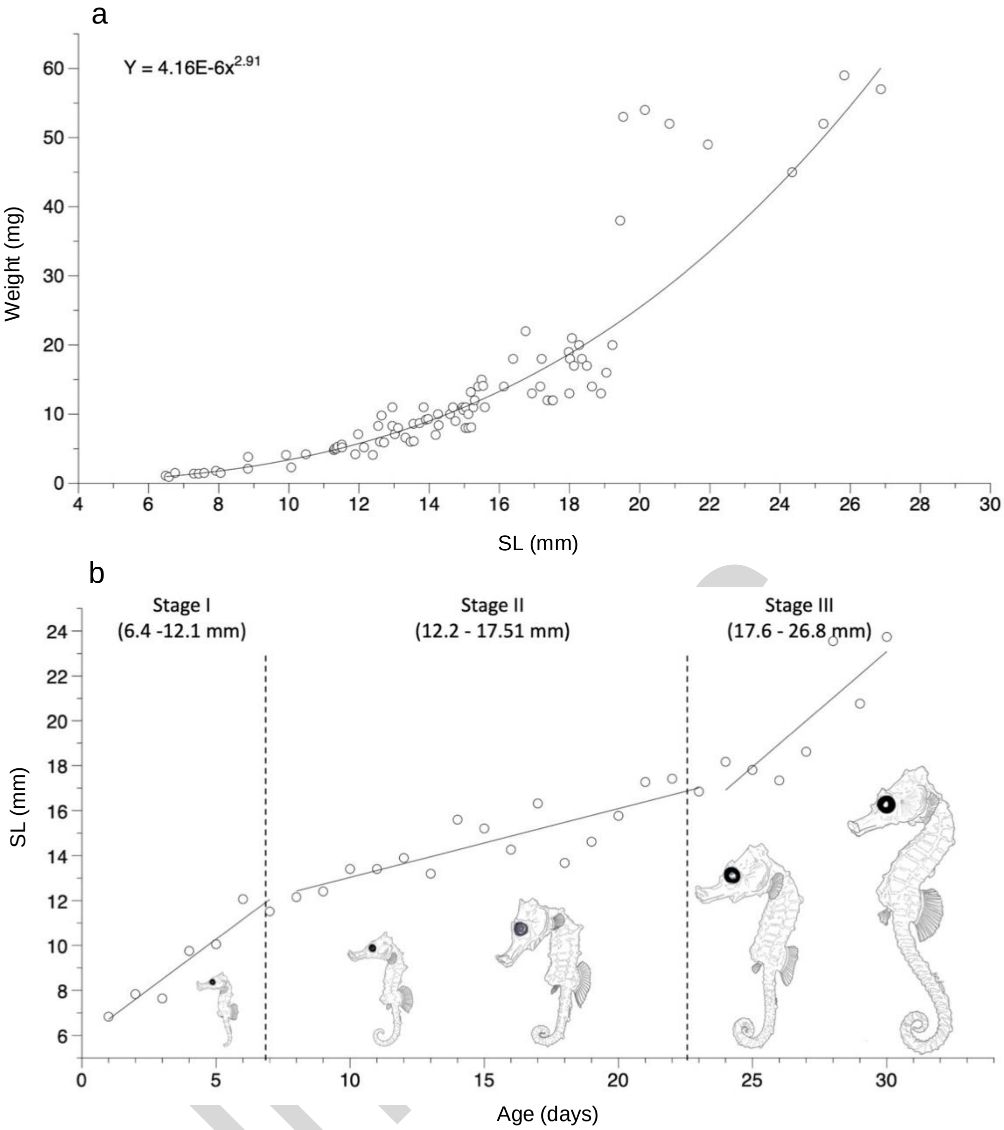


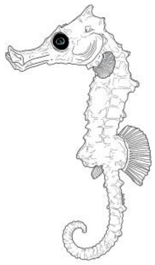
Figure 2. a) Length-weight relationship during the early development of the juvenile long-snout seahorse *Hippocampus reidi* (n = 90); b) relation between the standard length (SL) and age. Early growth was divided into three developmental stages denoted by two inflection points at 6 and 22 days (12.1 and 17.51 mm SL, respectively). Each point represents the mean (*n* = 3).

net height (CoH), orbital diameter (OrD), and postorbital length (PoL), were found to be isometric. The other body segments, including snout height (SnH), showed a negative growth coefficient (Table 1). The third stage was characterized by the positive allometry of TaL and SnH (*b* = 1.19 and *b* = 1.18, respectively). Other body segments, such as dorsal fin length (DfL) (*b* = 0.98), CoH (b = 1.04), and OrD (*b* = 1.07), showed isometric growth. The other body segments, including the SnL (*b* = 0.84), displayed negative allometry (Table 1).

Regarding the presence of an inflection point in the allometric growth during early development, the TrL, HeH, and PoL showed no inflection point, and these body segments exhibited a negative allometric growth with growth coefficients of 0.90, 0.88, and 0.78, respectively (Fig. 3).

The remaining body segments displayed an inflection point during development. All the inflection points occurred at stages I and II in an SL interval ranging from 10 to 17 mm. During the first stage three segments show an inflection point: the TaL shifted from a negative allometry (*b* = 0.86) to a positive allometric

Table 1. Allometric relationships of body segments and *t*-test parameters for variation of isometric growth during the three developmental stages of juvenile *Hippocampus reidi*. In parentheses is the standard length (SL) interval for each stage. CoH: coronet height; DfL: dorsal fin length; HeH: head height; HeL: head length; OrD: orbital diameter; PoL: postorbital length; SnH: snout height; SnL: snout length; TaL: tail length; TrL: trunk length. SE: standard error, d.f.: degrees of freedom.

	Body segment	Intercept (*a*)	Slope (*b*)	SE	*t*	d.f.	*P*
Stage I (6.4-12.1 mm)							
	HeL	0.32	0.95	0.065	-0.83	19	0.415
	TrL	-0.39	0.88	0.054	-2.22	19	0.039
	TaL	-0.53	1.13	0.044	2.95	19	0.008
	HeH	-0.70	0.83	0.097	-1.75	19	0.096
	DfL	-0.58	0.56	0.048	-9.16	19	0.0001
	SnL	-1.43	1.65	0.269	2.41	19	0.026
	SnH	-0.85	0.55	0.071	-6.33	19	0.0001
	CoH	-0.69	0.73	0.117	-2.30	19	0.032
	OrD	-0.88	0.63	0.091	-4.06	19	0.0006
	PoL	-0.64	0.62	0.096	-3.95	19	0.0008
Stage II (12.2-17.51 mm)							
	HeL	-0.48	0.80	0.050	-4.00	43	0.0002
	TrL	0.60	0.96	0.059	-0.67	43	0.501
	TaL	-0.49	1.12	0.047	2.55	43	0.014
	HeH	-1.00	1.10	0.097	1.03	43	0.308
	DfL	-0.64	0.62	0.067	-5.37	43	0.0001
	SnL	-0.46	0.89	0.087	-1.26	43	0.215
	SnH	-1.21	0.87	0.121	-1.07	43	0.290
	CoH	-0.95	0.93	0.127	-0.55	43	0.580
	OrD	-1.20	0.93	0.118	-0.59	43	0.560
	PoL	-1.05	0.99	0.138	-0.07	43	0.940
Stage III (17.6-26.8 mm)							
	HeL	-0.33	0.78	0.056	-3.93	20	0.001
	TrL	-0.35	0.86	0.068	-2.06	20	0.052
	TaL	-0.58	1.19	0.055	3.45	20	0.026
	HeH	-0.57	0.73	0.121	-2.23	20	0.037
	DfL	-1.08	0.98	0.101	-0.19	20	0.844
	SnL	-0.42	0.84	0.069	-2.32	20	0.030
	SnH	-1.62	1.18	0.153	1.18	20	0.250
	CoH	-1.07	1.04	0.119	0.34	20	0.740
	OrD	-1.38	1.07	0.144	0.48	20	0.630
	PoL	-0.88	0.85	0.143	-1.05	20	0.310

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growth (*b* = 1.17) at an SL of 10 mm (Fig. 4a). The HeL changed from an early isometry (*b* = 0.98) to a negative allometric growth (*b* = 0.79) at an SL of 11.7 mm (Fig. 4b). The SnL changed from a highly positive allometric growth (b = 1.74) to a negative allometry (*b* = 0.88) at an SL of 12 mm (Fig. 4c).

During the second stage, the remaining body segments changed from a negative allometry (*b* > 1) to an isometry (*b* = 1). The CoH displayed the inflection point at 12.5 mm SL, shifting from *b* = 0.69 to 1.00 (Fig. 5a). The inflection point of the OrD was observed at a SL = 12.9, with the growth coefficient changing from *b* = 0.63 to 0.98 (Fig. 5b). The growth coefficient of the SnH, changed from *b* = 0.56 to 1.00 at a SL of 15 mm (Fig. 5c). The inflection point of the DfL was detected at a SL of 17 mm, its growth coefficient changed from *b* = 0.55 to 0.99 (Fig. 5d).

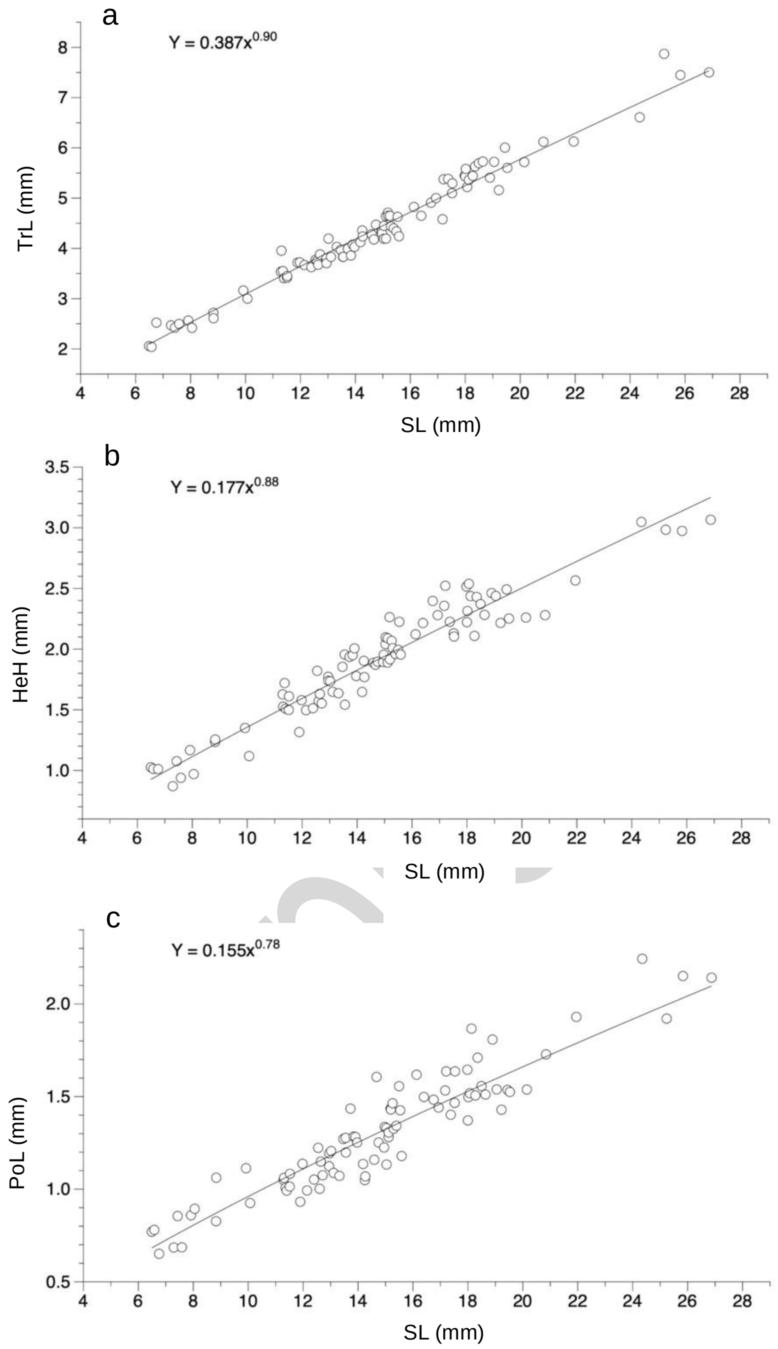

Figure 3. Allometric growth with no inflection points, denoting a monophasic growth during the early development of juvenile long-snout seahorse *Hippocampus reidi*. a) Trunk length (TrL), b) head height (HeH), c) postorbital length (PoL). SL: standard length.

DISCUSSION

The weight-length relationship observed during the early juvenile development of *H. reidi* in the present study showed an isometric growth coefficient *(b* = 2.91). Hora & Joyeux (2009) reported a similar growth coefficient (*b* = 2.94) for the weight-length relationship of *H. reidi* juveniles kept under culture conditions. These growth coefficients are higher than the ones reported for juvenile *H. kellogi* (*b* = 2.01) (Balasubramanian & Murugan 2017), *H. hippocampus* (*b* = 2.41), and *H. guttulatus* (*b* = 2.84) (Basusta et al. 2014). These lower growth coefficients may be related to the origin of the specimens, which were adults col-

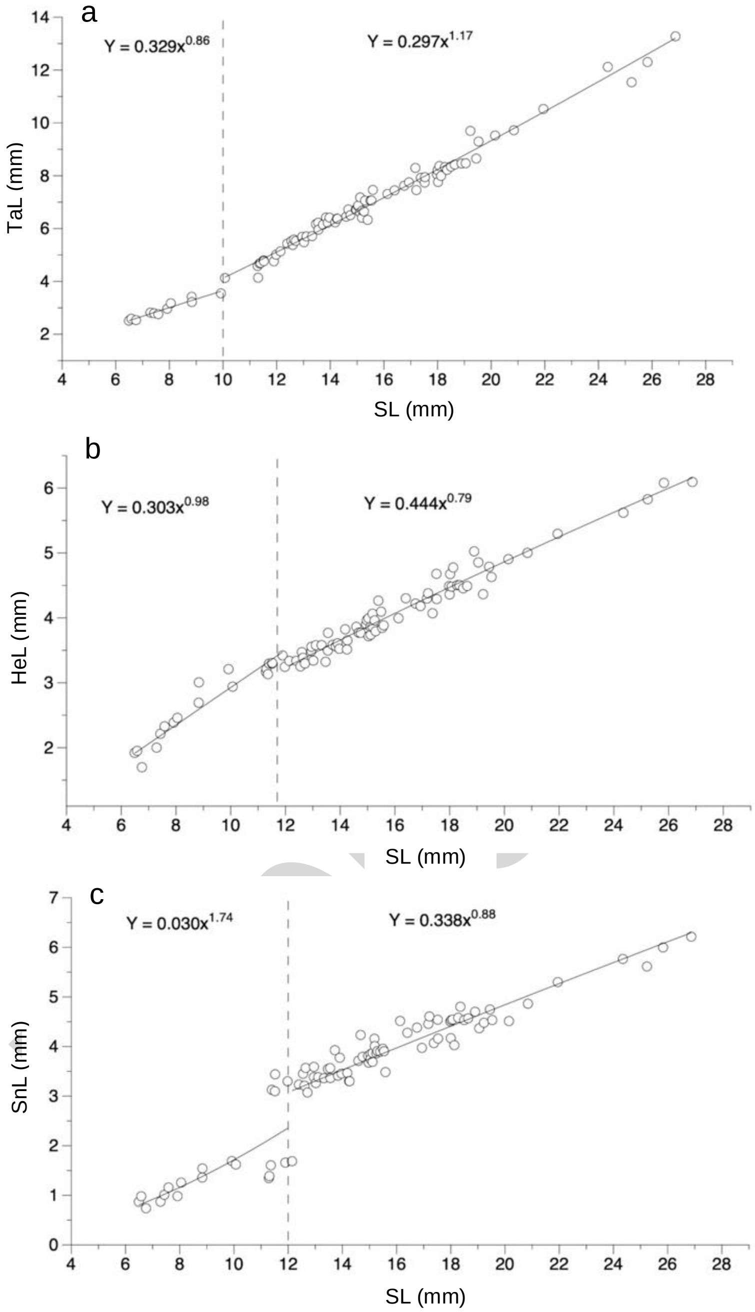

Figure 4. Allometric growth patterns and inflection points of a) tail length (TaL), b) head length (HeL), and c) snout length (SnL) during the early development of juvenile long-snout seahorse *Hippocampus reidi*. SL: standard length.

lected from the wild, where abiotic factors and feeding conditions are often unknown and usually less than optimal, affecting the growth and nutritional condition of seahorses. Furthermore, the weight-length relationship in fishes can be affected by several factors, including age, gonad maturation, diet, and developmental stage, among others (Hora & Joyeux 2009, Basusta et al. 2014).

The newly born juveniles of *H. reidi* in the present study show an average SL = 6.83 ± 0.52 mm, which is similar to the SL reported by Vincent (1990) (6.7 mm) and Olivotto et al. (2008) (7-7.5 mm), but slightly lower than the SL reported by Hora & Joyeux (2009) (8.2 mm) and Planas et al. (2021) (8.0-8.6 mm). These differences observed in the SL at birth may be related to variations in parental size, broodstock nutrition, and

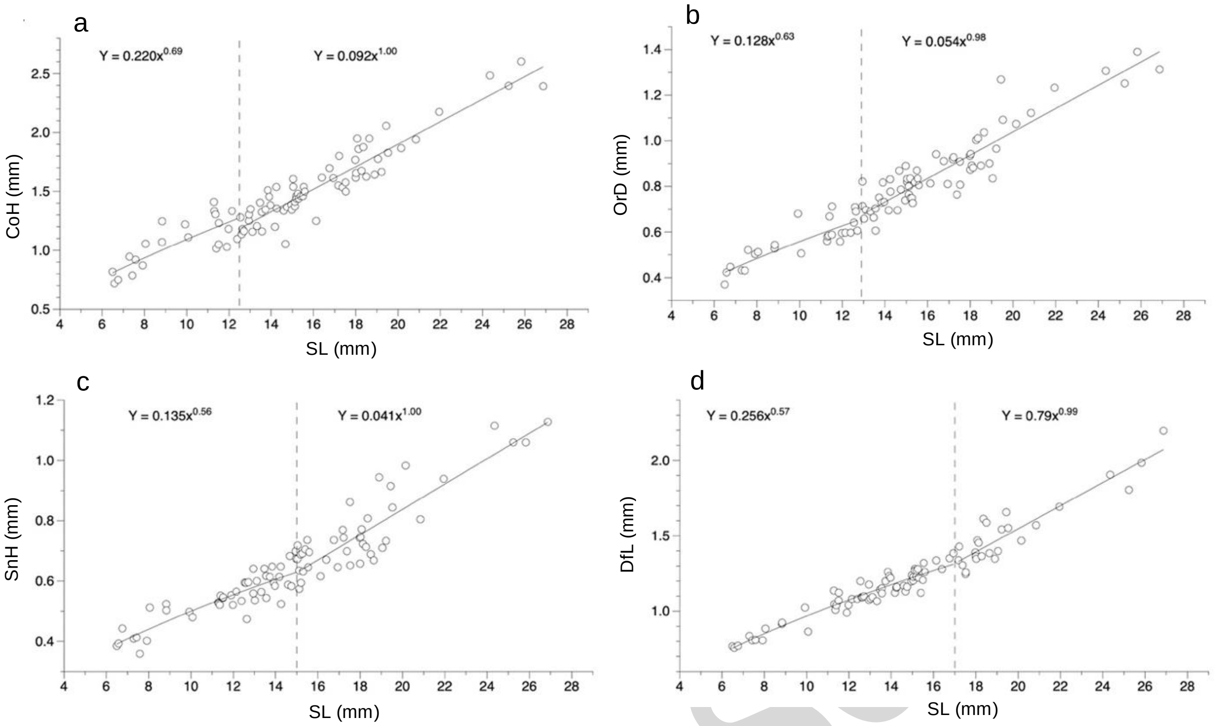

Figure 5. Allometric growth patterns and inflection points of a) coronet height (CoH), b) orbital diameter (OrD), c) snout height (SnH), and d) dorsal fin length (DfL) during the early development of juvenile long-snout *Hippocampus reidi*. SL: standard length.

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origin (culture or wild) among studies. However, the growth rate detected in our study was similar to that reported for the same species by Randazzo et al. (2018) during the same period. As in other seahorse species, *H. reidi* is born with the full form of a seahorse, although some body proportions differ from their adult form. In this sense, one of the strategies observed during early fish development to ensure survival implies a differential growth of body segments associated with primordial functions like feeding and swimming to avoid predation (Osse & van den Boogart 2004), which is explained by allometric growth (Gould 1966) and characterized by promoting major changes in body shape. Body segments, such as HeL and TaL, exhibit a high growth rate during early fish development (Osse et al. 1997), supporting the hypothesis that growth priorities are directed towards developing primary functions. After the initial period of accelerated growth (positive allometry), a tendency to isometry suggests that primary functions have been fulfilled (Osse & van den Boogaart 2004). This general growth pattern during early development has been described in other freshwater and marine teleost species (Gisbert et al. 2002, Martínez-Montaño et al. 2016, Peña et al. 2023), as well as in seahorses (Choo & Liew 2006, Peña & Zúñiga-Villarreal 2023), including *H. reidi* (present study).

The length of the corporal segments that define the SL in *H. reidi* (i.e. HeL, TrL, and TaL) displayed different growth coefficients. The HeL showed an isometric growth, coinciding with reports in other seahorses like the big-belly seahorse *Hippocampus abdominalis* Lesson, 1827 (Shi et al. 2023) and *H. kuda* (Choo & Liew 2006). On the other hand, in juveniles of the lined seahorse *H. erectus* Perry, 1810, the HeL displayed positive allometry (Bergert & Wainwright 1997).

The growth of the head section observed in *H. reidi* juveniles can be associated with the development of organs involved in integrating sensory functions, such as the brain, and in feeding and respiration, like the eyes and branchial arches, respectively (Gagnat et al. 2016). The allometric pattern of the OrD and the SnL detected in this study supports this hypothesis. Additionally, the early ossification of the cephalic bones has been reported in seahorses, which may contribute to head growth (Sun et al. 2021, Shi et al. 2023). Seahorses display pivot feeding (Van Wassenbergh et al. 2009), which consists of a combination of head rotation and suction by the snout (Van Wassenbergh et al. 2014).

Gemmel et al. (2013) reported that head growth and morphology in *H. zosterae* provide a hydrodynamic advantage during pivot feeding, enabling them to capture elusive prey, such as copepods or *Artemia* nauplii. Concomitantly with the snout growth, the expansion of the tip of the snout during feeding produces a pressure reduction inside the mouth cavity, increasing the speed of the water flux during suction and feeding success (Sun et al. 2021). In the wild, seahorses show a diurnal feeding activity, depending mostly on visual stimulation (Bergert & Wainwright 1997, Kuiter 2000, Mosk et al. 2007). It has been reported that the eye structure in *H. reidi* is completed from hatching and includes the cornea, the lens, the iris, the retinae, the optic nerve, and the sclera. In the retina, cones and rods are already present (Novelli et al. 2015), indicating a fully developed visual system (van Wassenbergh et al. 2009). Moreover, the OrD increases during growth, accompanied by a concomitant proliferation of neural connections in the retinal layers and photoreceptors, which promotes visual acuity (Otteson & Hitchcock 2003, Hitchcock & Raymond 2004). Furthermore, seahorse eyes can move independently on either side of the head, increasing the field of vision during feeding.

Unlike the HeL, the TrL in *H. reidi* showed negative allometric growth, which seems to be a common tendency during the early development of fish, as has been reported in many species (Fuiman 1983, Osse et al. 1997, van Snik et al. 1997, Gisbert 1999, Gisbert et al. 2002, Martínez-Montaño et al. 2016, Saemi-Komsari et al. 2018). However, in other seahorses like *H. ingens* (Peña *unpubl. data*) and *H. kuda* (Choo & Liew 2006), the TrL showed an isometric growth (b = 0.96 and b = 1.0, respectively). In the case of *H. reidi*, this negative allometry in the trunk could be related to the early presence of all the organs in this body segment, suggesting that no further major transformations in TrL are necessary. Indeed, Novelli et al. (2015) described the development of *H. reidi* from birth to 30 days. They mentioned that all the organs in the trunk section are well-formed at birth, including a developed digestive tract, an intestinal valve, the liver, the pancreas, the gas bladder, and an intestinal loop that occurs at eight days. The same internal structure has been reported for *H. guttulatus*, characterized by a folded intestine and the first intestinal loop emerging at 10 days (Randazzo et al. 2018).

The TaL in *H. reidi* showed positive allometry during the studied period. At birth, seahorses show an active pelagic lifestyle and eventually change to a more passive, semi-static benthic lifestyle when they can hold to a substrate using their prehensile tail (Foster & Vincent 2004), suggesting that to adapt to their final lifestyle properly, seahorses must prioritize the development of a long and strong tail to allow a firm grip to a substrate to avoid being dragged by currents, explaining the positive allometry observed in this segment in all developmental stages of *H. reidi*. Additionally, the length of the dorsal fin accelerates its growth in individuals of 20 mm SL, which directly contributes to the swimming capacity in the water column and the maneuverability of juveniles while attached to a substrate. Together, both segments contribute to avoiding the dragging of currents and developing the hunting method based on the ability to stay at a fixed point and wait for the prey (Foster & Vincent 2004). Peña & Zúñiga-Villarreal (2023) reported that in the Pacific seahorse *H. ingens*, the TaL displayed a positive allometric growth (b = 1.11) during early development. However, Choo & Liew (2006) reported that the TaL in *H. kuda* exhibited isometric growth (b = 1.08); however, their analysis spanned only four months, and no distinction was made between allometric growth during different developmental stages.

The occurrence of inflection points during the growth of the body segments is a common feature during the early allometric growth of fish (Gisbert 1999, Peña & Dumas 2009, Kupren et al. 2014, Martínez-Montaño et al. 2016, Peña et al. 2023), including seahorses (Choo & Liew 2006, Peña & Zúñiga-Villarreal 2023). However, they are not present in all the body segments. In the present study, the HeH, TrL, CoH, and PoL did not show an inflection point. In other syngnathids, such as *H. ingens* (Peña *unpubl. data*), only the PoL shows an inflection point. In *H. kuda* (Choo & Liew 2006), the TrL, TaL, HeH, HeL, and the length of the dorsal fin do not show an inflection point. In these cases, monophasic growth was considered for these body segments during early development due to the low environmental pressures faced by the fish during this stage, with no major changes in growth speed or body form observed (Kupren et al. 2013).

On the other hand, when present, inflection points denote a change in the growth speed and usually induce a change in body form during growth (Osse & Van den Boogaart 2004). In the present study, the HeL, TaL, DfL, OrD, SnL, and SnH show an inflection point. In a similar study, only the SnL, DfL, and the eye diameter showed an inflection point (Choo & Liew 2006), while in *H. ingens* all body segments showed an inflection point except for the PoL, and in the case of the SnH two

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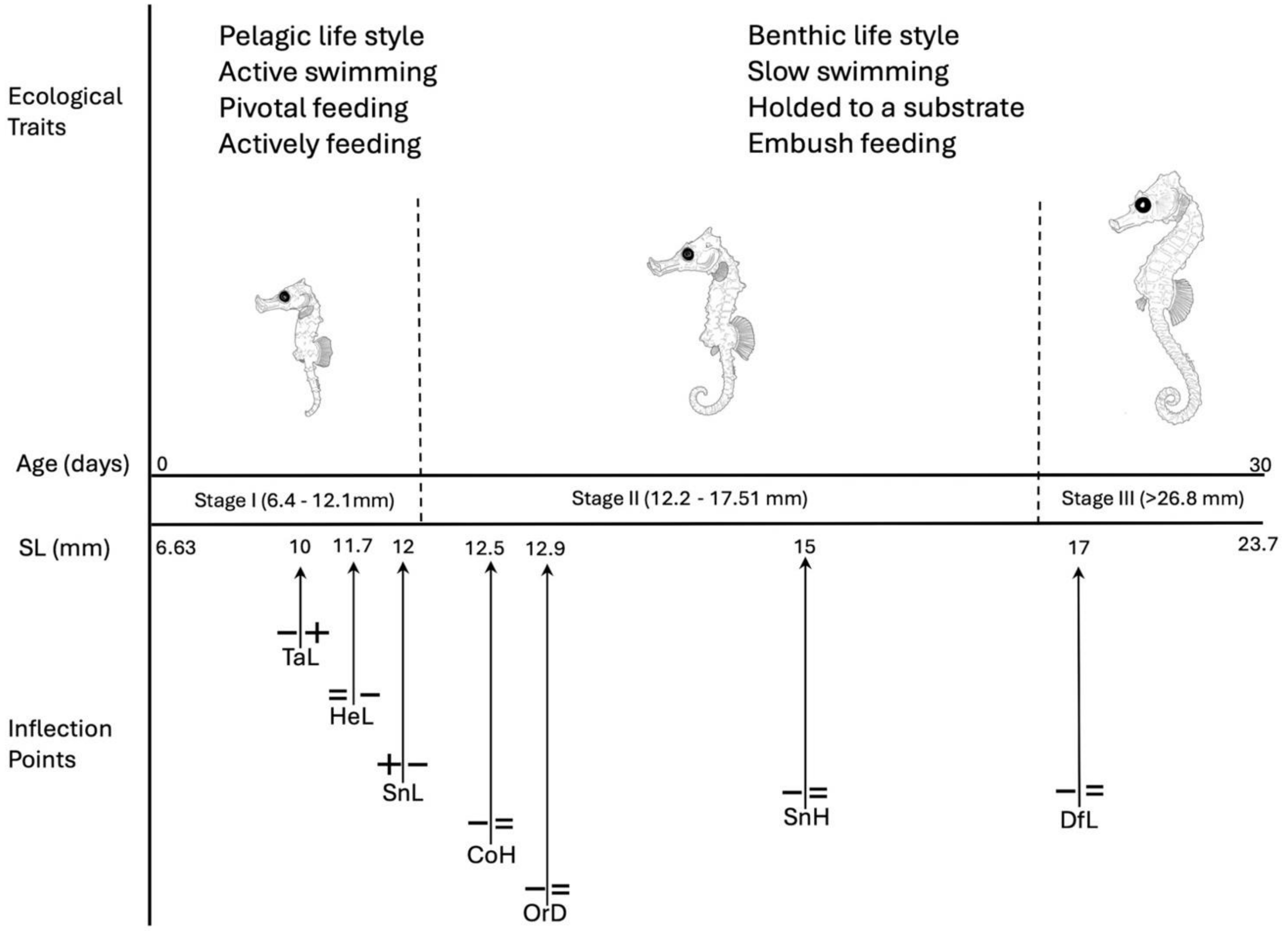

Figure 6. Developmental events and inflection points during the juvenile stages of long-snout seahorse *Hippocampus reidi*. CoH: coronet height, DfL: dorsal fin length, HeL: head length, OrD: orbital diameter, SnH: snout height, SnL: snout length, TaL: tail length, SL: standard length.

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inflection points were evident at 10 and 26 mm SL (Peña *unpubl. data*).

Although the presence of inflection points is a usual feature during the early growth of teleost fish, the length at which they appear varies greatly between species. For instance, in *H. kuda*, the inflection points appeared at an interval of 20-30 mm SL (Choo & Liew 2006), while in the present study, they all appeared in a narrow interval from 9 to 11 mm SL (Fig. 6). In other teleost has been reported that when the inflection points occur in a narrow SL interval they coincide with important moments during initial development and most of the time coincide with changes in lifestyle or developmental stage, like from preflexion to flexion stages (Peña et al. 2023) and also coincides with major changes in physiological capabilities of the fishes (Osse & van den Boogaart 2004, Somarakis & Nikolioudakis 2010). In the case of *H. reidi*, the fact that the inflection points occurred within 2 mm SL suggests that during this SL interval, important changes occur in the growth rate and body shape coinciding with the end of stage I and the start of stage II with important lifestyle changes like a reduction in swimming activity, holding on to a substrate and ambush feeding (Fig. 6).

In a pragmatic approach, the developmental stages and the information generated in this study have implications for the culture conditions of the species, which could serve as a reference point when evaluating the effectiveness of new culture conditions or the adequacy of different prey types. In addition, the pelagic lifestyle in stage I suggests that a higher prey density is necessary to reduce the juveniles' search time and energy expenditure, promoting a higher encounter rate and increasing feeding efficiency. On the other hand, during the second and third stages, following the inflection points, a semi-stationary benthic lifestyle emerges, characterized by increased attachment to a substrate. It may be necessary to increase the water flow rate to promote a homogeneous distribution of prey in the water column. It will promote the new feeding style among juveniles, which will be reflected in higher growth rates. Nevertheless, it will be interesting to evaluate the development of other systems, such as the visual and digestive systems, during these stages to generate more information that could be useful in adapting the culture conditions to the biological and physiological capabilities of the juveniles and to support the previous hypothesis.

Credit author contribution

R. Peña: conceptualization, methodology, data analysis, interpretation, writing-original draft, writing-review & editing, funding acquisition; R.P. Mata-Miranda: juvenile measurement and morphometric analysis; E. Zúñiga-Villarreal: juvenile rearing and sampling. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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