Chela shape asymmetry in the *Ranina ranina* (Linnaeus, 1758) from two coastal island populations in the Philippines

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Abstract. Fluctuating asymmetry (FA) of bilateral morphological traits has been widely used as a descriptive indicator of developmental instability in aquatic organisms. In crustaceans, chelae are functionally important structures involved in feeding, defense, and reproduction, and their morphology may reflect variation in developmental outcomes among individuals and populations. The red frog crab, *Ranina ranina* (Linnaeus, 1758), is a commercially exploited species in the Philippines. However, quantitative information on morphological asymmetry across its populations remains limited. This study examined chela shape asymmetry in *R. ranina* collected from two geographically separated island populations in Mindanao, Philippines. Landmark-based geometric morphometric methods were applied to bilateral chelae of male and female *R. ranina* to quantify fluctuating and directional asymmetry (DA) using Procrustes superimposition and Procrustes analysis of variance. Principal component analysis (PCA) was performed to visualize patterns of shape asymmetry. Significant FA was detected across populations and sexes, indicating variation in developmental stability under natural conditions. DA was also observed in specific population-sex groups, suggesting consistent left-right differences in chela morphology. Although causal factors were not directly assessed, the observed patterns demonstrate the utility of chela shape asymmetry as a sensitive morphological descriptor for comparative analyses. These findings contribute to the growing application of geometric morphometrics and asymmetry analyses in crustacean studies and highlight their value as non-lethal tools for describing morphological variability in exploited marine species.
Keywords: bilateral symmetry, crustacean morphology, developmental instability, fisheries bioindicator, fluctuating asymmetry, geometric morphometrics, Procrustes ANOVA.

Introduction. Assessing the biological condition of exploited marine populations requires indicators that capture variation in growth, development, and morphological stability under natural conditions. In many tropical fisheries, conventional stock-assessment approaches based on long-term catch data, age structure, or experimental surveys are often limited by data availability, logistical constraints, or high environmental variability. As a result, alternative biological descriptors are increasingly used to complement traditional fisheries assessments (Mann & Lazier, 2006; Graham et al., 2010). Morphological indicators derived from geometric morphometrics have emerged as valuable indicators because they can document subtle phenotypic responses that might be missed using traditional fisheries metrics (Graham et al., 2010; Klingenberg, 2015; Pertoldi & Kristensen, 2015; Benítez et al., 2020).

Morphological traits integrate genetic, environmental, and physiological influences accumulated during development, thereby making them valuable indicators of population-level variation. Among these, fluctuating asymmetry (FA) refers to small, random deviations from perfect bilateral symmetry and is commonly interpreted as an indicator of developmental instability when buffering mechanisms are disrupted during growth (Palmer

& Strobeck, 1986; Graham et al., 1993; Graham et al., 2010; Graham, 2021). FA has been applied across a wide range of aquatic organisms, including fishes, mollusks, insects, and crustaceans, to describe developmental variation associated with environmental heterogeneity, biological stress, or functional constraints (Swaddle, 2003; Ducos & Tabugo, 2015; Pojas & Tabugo, 2015; Saura et al., 2021). Recent reviews indicate that FA should be considered primarily an indicator of developmental instability and phenotypic variation rather than unambiguous evidence of environmental stress. FA offers a strong framework for comparative population studies when assessed using landmark-based geometric morphometrics, while reducing the disadvantages of classical linear morphometrics (Benítez et al., 2020).

Recent advances in geometric morphometrics have improved the resolution and reliability of asymmetry analyses by preserving spatial relationships among landmarks and allowing multivariate quantification of shape differences (Graham et al., 2010; Rohlf, 2010). Landmark-based methods combined with Procrustes analysis of variance enable the separation of FA, directional asymmetry (DA), and measurement error, providing a robust framework for studying bilateral traits (Graham et al., 2010). These approaches have been increasingly adopted in aquatic research, where FA is interpreted conservatively as a descriptive indicator rather than definitive evidence of specific stressors (Pojas & Tabugo, 2015; Hingabay, 2016).

In decapod crustaceans, chelae are multifunctional appendages used in feeding, defense, and social interactions, and their morphology often differs between sexes and among populations (Schenk & Wainwright, 2001; Hampton et al., 2014). Such functional importance makes chelae suitable structures for investigating shape variation and asymmetry. DA in chelae has been reported in several crustacean species and is commonly attributed to functional lateralization or differential usage, although its expression may vary among populations and environmental contexts (Schenk & Wainwright, 2001; Costa et al., 2024). Recent morphometric studies on marine crustaceans also demonstrate that chelae morphology is sensitive to both intrinsic biological variation and environmental heterogeneity, further highlighting the utility of geometric morphometric approaches for comparative population studies (Cabuga et al., 2025)

The red frog crab, *Ranina ranina* (Linnaeus, 1758) is a commercially important species distributed throughout the Indo-West Pacific and is supported by artisanal and small-scale fisheries in the Philippines. Previous studies on *R. ranina* have focused primarily on aspects of fishery biology, reproduction, feeding ecology, and general morphology (Tahil, 1983; Tito & Alalano, 2008; Baylon & Tito, 2012; Matondo & Demayo, 2015). However, quantitative analyses of chela shape asymmetry and developmental stability in this species remain limited, particularly using landmark-based geometric morphometric approaches.

The present study applies geometric morphometric methods to quantify chela shape asymmetry in *R. ranina* from two geographically separated island populations in Mindanao, Philippines. Specifically, this study aims to: (1) assess fluctuating and DA in chela morphology; (2) compare asymmetry patterns between populations and sexes; and (3) evaluate the applicability of chela shape asymmetry as a descriptive indicator of morphological variation under natural conditions.

Material and Method

Study area and sample collection. Chela samples of *R. ranina* were obtained from two major fishing areas in Mindanao, Philippines: the coastal waters of Sacol Island, Zamboanga City (Moro Gulf), and Siargao Island, Surigao del Norte (Philippine Sea) (Figure 1). These sites are geographically separated fishing grounds with distinct oceanographic conditions.

R. ranina samples were collected straight from local crab fishermen who were allowed to work in the areas where sampling was conducted. Sex was determined based on abdominal morphology. From Sacol Island, chelae were taken from 47 females and 49 males. From Siargao Island, the chelae were obtained from 52 females and 50 males. The

study considered only the whole chelae that showed no visible damage to avoid making them appear different.

Every chela was carefully separated, cleaned of dirt, dried in air, and placed in labelled, sealed plastic bags for imaging and morphometric analysis.

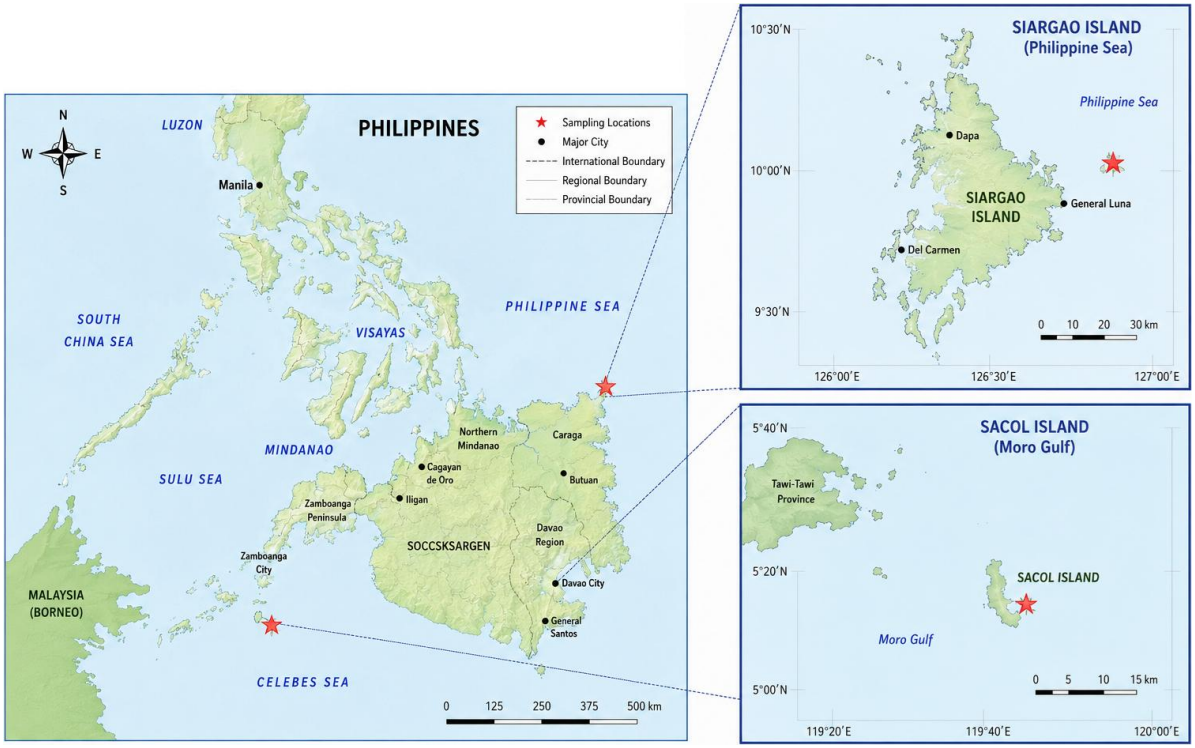


Figure 1. Map showing the geographic locations of the two fishing grounds in Mindanao, Philippines: Sacol Island (Moro Gulf) and Siargao Island (Philippine Sea), where chela samples of *Ranina ranina* were collected.

Imaging procedure. A Fujifilm FinePix S2000HD/S2100HD digital camera set to macro mode was used to photograph each chela. The camera was mounted on a tripod to ensure consistent distance and orientation across all samples. Images were taken in the same lighting conditions to reduce distortion and shadows. All chelae were positioned with the dorsal surface facing upwards, and the orientation of the left chela was standardized for imaging purposes. Three replicate images were obtained for each specimen to account for digitization error.

Landmark Acquisition and Geometric Morphometric Analysis. Geometric morphometric techniques based on landmarks were used to quantify variation and asymmetry in chela shape. A total of 34 homologous anatomical landmarks were identified and digitized on the dorsal surface of each chela (Figure 2; Table 1). These landmarks were chosen because they were consistently present across all specimens and were important for understanding chela morphology.

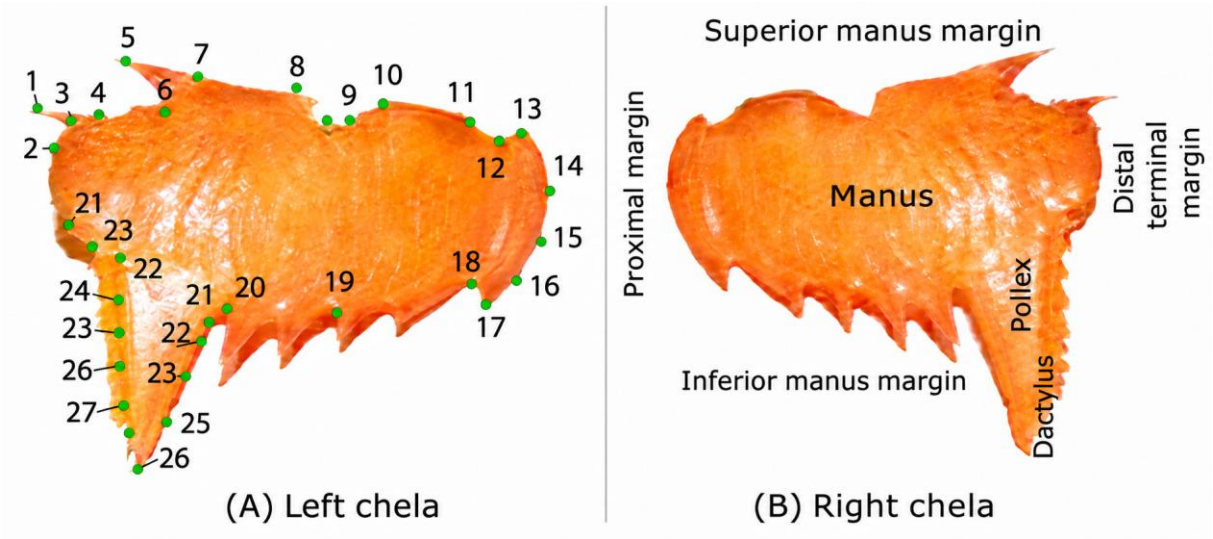


Figure 2. Dorsal view of the chela of *Ranina ranina* illustrating the configuration and numbering of the 34 homologous landmarks used for landmark-based geometric morphometric asymmetry analysis.

We used TPSdig2 version 2.16 (Rohlf 2010) to digitize the landmarks. To reduce inter-observer error and check the reliability of the measurements, the same researcher digitized each image three times on different days.

Measurement of fluctuating and directional asymmetry. To evaluate bilateral asymmetry, landmark configurations of the left and right chelae were subjected to generalized procrustes analysis (GPA), which eliminates the effects of size, position, and orientation, producing shape variables suitable for statistical analysis (Rohlf, 2010). Reflected and relabeled landmark configurations were incorporated to generate a bilaterally symmetrical Procrustes consensus shape.

FA and DA were assessed through Procrustes analysis of variance (ANOVA), adhering to standardized methodologies for the evaluation of symmetry and asymmetry in geometric morphometric data (Palmer and Strobeck, 1986; Graham et al., 2010; Pertoldi & Kristensen, 2015). The Procrustes ANOVA decomposed shape variation into the following components: individuals (symmetric variation), sides (DA), individual × side interaction (FA), and measurement error.

To assess the importance of FA and DA, we compared the mean squares for each component to the measurement error. Individual × side interactions that were highly significant were taken as evidence of FA, while significant side effects were taken as evidence of DA.

Visualization of Shape Variation. We performed principal component analysis (PCA) on Procrustes-aligned tangent coordinates to examine how chelae shapes change when asymmetrical. PCA identified the principal axes of shape variation contributing to deviations from bilateral symmetry. Similar landmark-based PCA approaches have been successfully applied in Philippine freshwater fishes for evaluating FA (Saura et al., 2021). We used thin-plate spline interpolation to create deformation grids that showed how the shape changed along the main components. These grids showed how the landmarks moved compared to the symmetrical consensus configuration (Graham et al., 2010; Pertoldi & Kristensen, 2015).

Table 1

Anatomical descriptions of the 34 homologous landmarks digitized on the dorsal aspect of the chela of *Ranina ranina* for landmark-based geometric morphometric analysis

Landmarks	*Landmark description*
1	Superior margin insertion base of the major dactyl
2	Anterior base, distal spine on the superior manus margin
3	Tip of the distal spine
4	Posterior base, distal spine superior margin
5	Anterior base of the superior spine
6	Tip of the superior spine
7	Posterior base of the superior spine
8	Inner base superior articulation joint propodus-carpus
9	Superior articulation gap point propodus-carpus
10	Outer end superior articulation points propodus-carpus
11	Inner base inferior articulation joint propodus-carpus
12	Inferior articulation gap point propodus-carpus
13	Proximal point, superior manus margin
14	Point on the proximal lateral margin rectilinear to the mid-distal lateral margin
15	Point on the proximal lateral margin rectilinear to the anterior base of the pollex
16	Point on the proximal lateral margin rectilinear to the base of the inferior proximal spine
17	Tip proximal spine at the inferior margin
18	Anterior base of the inferior proximal spine of the inferior margin
19	Midpoint between 2nd and 3rd spines at the inferior margin
20	Anterior base of the major spine along the inferior margin
21	Posterior base of the pollex
22	Rectilinear to the point between the 3rd and 4th chela tooth
23	Rectilinear to point between the 4th and 5th chela tooth
24	Rectilinear to the point between the 5th and 6th chela tooth
25	Rectilinear to the point between the 6th and 7th chela tooth
26	Distal point of the pollex
27	Point parallel to the point between the 6th and 7th chela tooth
28	Point along the pollex corresponding to the point between the 5th and 6th chela tooth
29	Point along the pollex corresponding to the point between the 4th and 5th chela tooth
30	Point along the pollex parallel to the point between the 3rd and 4th chela tooth
31	Point along the pollex corresponding to the point between the 2nd and 3rd chela tooth
32	Anterior base of the pollex
33	Base of the chela tooth
34	Inferior margin insertion base of the major dactyl

Statistical analysis. We used the Symmetry and Asymmetry in Geometric Data (SAGE) framework and related morphometric software to perform geometric morphometric analyses, including Procrustes superimposition, Procrustes ANOVA, and PCA. Statistical results were analyzed using standard methods for morphometric asymmetry analysis in biological and fisheries research.

Results

Procrustes analysis of variance. Procrustes analysis of variance (ANOVA) revealed significant chela shape asymmetry in *R. ranina* across both populations and sexes (Table 2). In all population-sex groupings, the individual × side interaction term was highly significant, indicating the presence of FA in chela morphology.

For the Sacol Island population, females exhibited significant FA ($F = 3.8529$, $p < 0.001$), while DA was not significant. In contrast, males from Sacol Island showed highly significant FA ($F = 5.2701$, $p < 0.001$) and significant DA ($F = 3.6147$, $p < 0.001$).

In the Siargao Island population, both females and males displayed highly significant FA (females: $F = 5.1085$, $P < 0.001$; males: $F = 4.1989$, $p < 0.001$). DA was

significant only in females from Siargao Island (F = 2.5431, p < 0.001), whereas males did not show significant DA.

Measurement error was consistently lower than both fluctuating and DA components across all analyses, indicating reliable landmark digitization and shape measurement.

Table 2

Procrustes ANOVA of chela shape asymmetry in *Ranina ranina* (Sacol and Siargao Islands)

Effect	*SS*	*DF*	*MS*	*F*	*p*	*Remarks*
Sacol females						
Individuals	0.199	2,880	6.91E-05	1.0572	0.068	ns
Sides (DA)	0.004	64	5.46E-05	0.8356	0.821	ns
Individuals x Sides (FA)	0.188	2,880	6.54E-05	3.8529	p < 0.001	hs
Measurement error	0.199	11,776	1.70E-05	-	--	
Sacol males						
Individuals	0.151	3,072	4.93E-05	1.0793	0.017*	s
Sides (DA)	0.011	64	0.000165	3.6147	p < 0.001	hs
Individuals x Sides (FA)	0.140	3,072	4.56E-05	5.2701	p < 0.001	hs
Measurement error	0.109	12,544	8.66E-06	-	--	
Siargao females						
Individuals	0.124	3,264	3.79E-05	0.8561	1	ns
Sides (DA)	0.007	64	0.000113	2.5431	3.17E-10	hs
Individuals x Sides (FA)	0.145	3,264	4.43E-05	5.1085	p < 0.001	hs
Measurement error	0.115	13,312	8.67E-06	--	0.11546	
Siargao males						
Individuals	0.196	3,136	6.26E-05	0.8678	0.99996	ns
Sides (DA)	0.002	64	3.34E-05	0.4627	0.99992	ns
Individuals x Sides (FA)	0.226	3,136	7.22E-05	4.1989	p < 0.001	hs
Measurement error	0.220	12,800	1.72E-05			

Note: SS - sum of squares; DF - degrees of freedom; MS - mean square; F - F-statistic; DA - directional asymmetry; FA - fluctuating asymmetry; ns - not significant; s - significant (p < 0.05); hs - highly significant (p < 0.001).

To facilitate comparison of asymmetry patterns among groups, the F-values associated with FA and DA were summarized graphically (Figure 3). Higher FA values relative to DA indicate that random developmental deviations contributed more substantially to chela shape variation than consistent left-right differences across populations and sexes. FA values were consistently higher than DA values across all population-sex groups. The highest FA was observed in Sacol Island males (F = 5.2701), followed by Siargao Island females (F = 5.1085), Siargao Island males (F = 4.1989), and Sacol Island females (F = 3.8529). In contrast, DA values were generally lower, with significant DA observed primarily in Sacol Island males (F = 3.6147) and Siargao Island females (F = 2.5431). These results indicate that FA contributed more substantially to chela shape variation than DA in both populations.

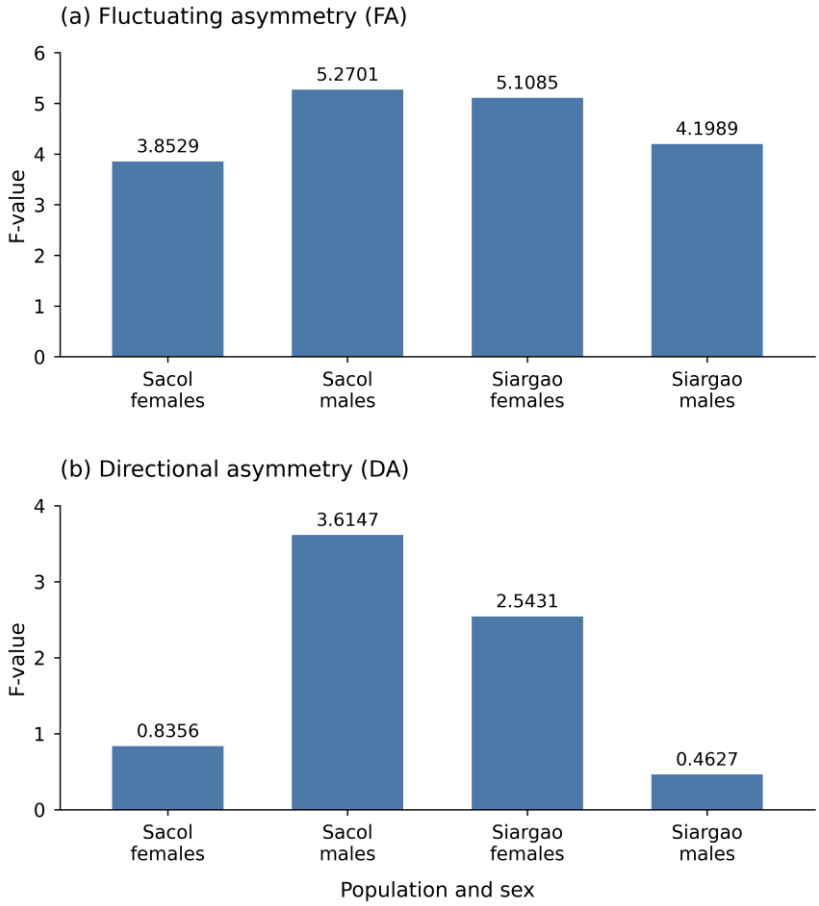


Figure 3. Comparative asymmetry patterns in the chela morphology of *Ranina ranina* from Sacol Island and Siargao Island, Philippines. (A) Fluctuating asymmetry represented by Procrustes ANOVA F-values derived from the individual × side interaction effect. (B) Directional asymmetry represented by Procrustes ANOVA F-values derived from the side effect.

Principal component analysis of asymmetry. PCA of Procrustes-aligned tangent coordinates summarized chela shape variation associated with asymmetry in both populations and sexes (Table 3). For all groups, the first five to six principal components accounted for more than 69% of total shape variance related to departures from bilateral symmetry. PC1 accounted for the largest proportion of asymmetry-related variation, followed by PC2, PC3, PC4, and PC5. Collectively, these components explained between 69.13% and 72.05% of total shape variation across populations.

Table 3

PCA results describing chela shape variation in *Ranina ranina* from Sacol and Siargao Islands. Only components explaining > 5% of total variance are shown

Sites	*Sex*	*PC1 (%)*	*PC2 (%)*	*PC3 (%)*	*PC4 (%)*	*PC5 (%)*	*PC6 (%)*	*Total variance (%)*
Sacol	Female	30.81	14.01	11.90	9.11	6.22	-	72.05
Island	Male	29.13	11.36	9.40	7.90	7.47	5.40	70.86
Siargao	Female	28.52	18.83	8.85	7.33	5.60	-	69.13
Island	Male	33.47	12.37	10.54	8.86	5.80	-	71.04

Note: PC - principal component; values represent the percentage of total shape variance explained by each principal component derived from Procrustes-aligned landmark coordinates.

In the Sacol Island population, the first five principal components explained 72.05% of the total variance in females and 70.86% in males. In the Siargao Island population, the first five principal components explained 69.13% of the total variance in females and 71.04% in males.

Patterns of shape variation. In Sacol Island females, chela asymmetry was primarily associated with deformation along the superior distal margin of the manus and the pollex. Additional variation was observed near the articulation between the manus and propodus and along the inferior margin of the chela (Figure 4A). In Sacol Island males, asymmetry was concentrated in the distal region of the superior manus margin, including the distal and superior spines, as well as along the pollex margins and distal tip (Figure 4B).

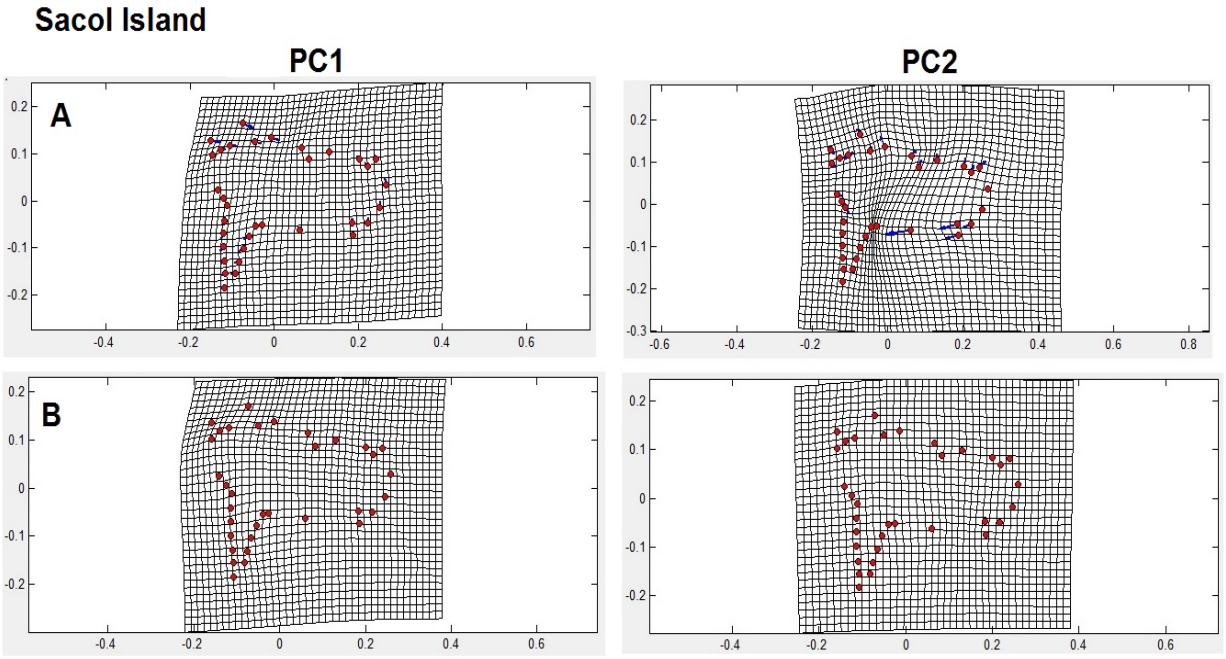


Figure 4. Principal component analysis (PCA)-derived deformation grids illustrating fluctuating asymmetry in chela shape of *Ranina ranina* from Sacol Island: (A) females and (B) males. Deformations represent landmark displacements relative to the bilaterally symmetric consensus configuration.

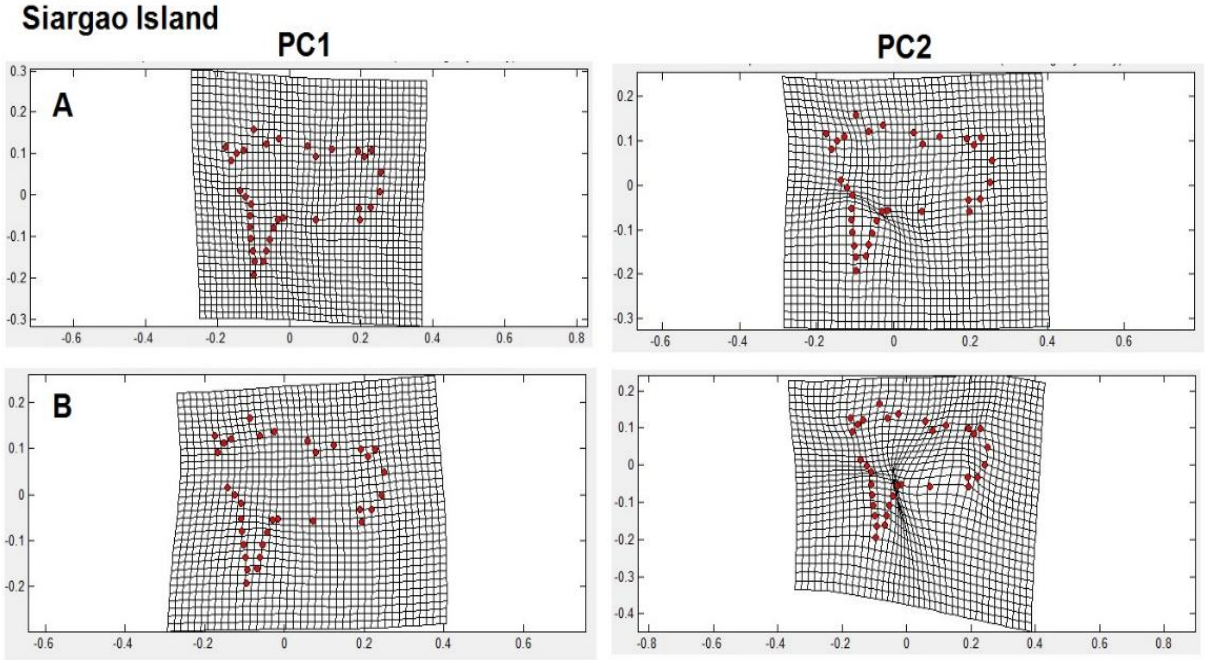


Figure 5. Principal component analysis (PCA)-derived deformation grids illustrating fluctuating asymmetry in chela shape of *Ranina ranina* from Siargao Island: (A) females and (B) males. Deformations represent left-right deviations from the bilaterally symmetric consensus shape.

In the Siargao Island population, females exhibited marked asymmetry in the shape of the pollex and along the proximal region of the superior manus margin, with variation extending toward the inferior dactyl attachment area (Figure 5A). Males from Siargao Island showed asymmetry primarily in the length and compression of the distal and superior spines, as well as along the pollex (Figure 5B).

Deformation grids derived from thin-plate spline interpolation illustrated these patterns of landmark displacement relative to the bilaterally symmetric consensus shape (Figures 4 and 5).

Discussion

Chela shape asymmetry and developmental instability. This study demonstratess fluctuating and, in some groups, DA in chela morphology of *R. ranina* from two island populations in Mindanao, Philippines. FA refers to small, random deviations from perfect bilateral symmetry and is commonly interpreted as an indicator of developmental instability arising from genetic, environmental, or physiological perturbations during growth (Palmer & Strobeck, 1986; Graham et al., 2010). The significant FA detected in this study indicates that chela development in *R. ranina* is not perfectly buffered against such perturbations under natural conditions.

Recent studies applying landmark-based geometric morphometrics have demonstrated the usefulness of FA as a descriptive indicator of developmental instability in aquatic organisms, including fishes, mollusks, and crustaceans, when interpreted conservatively and without attributing specific causal agents (Ducos & Tabugo, 2015; Klingenberg, 2015; Pojas & Tabugo, 2015; Hingabay, 2016; Saura et al., 2021). These studies emphasize FA as a comparative and population-level descriptor rather than direct evidence of environmental degradation. Similar applications have been reported for Philippine freshwater fishes, indicating that FA is a useful comparative descriptor of population-level developmental stability (Lecera et al., 2015).

Recent syntheses have highlighted that FA should not be used as a direct proxy for pollution or habitat degradation, but rather as an integrated manifestation of developmental instability due to multiple interacting genetic and environmental influences. Thus, FA is now viewed as a relative indicator of developmental precision that is most informative when combined with ecological and population-level information (Benítez et al., 2020).

Population- and sex-related variation in asymmetry. Differences in chela asymmetry were observed between populations and between sexes. Population-level variation in FA is consistent with differences in local environmental conditions, habitat characteristics, or population histories; however, the present observational data do not allow direct attribution to specific stressors. Similar population-specific morphological variation has been reported in crustaceans from contrasting habitats, where environmental heterogeneity and geographic separation were suggested as potential contributing factors (Hampton et al., 2014; Costa et al., 2024). Similar patterns of population-level morphological variation have been described in aquatic organisms using landmark-based geometric morphometrics, where differences among populations have been attributed to the combined effects of local environmental conditions, habitat characteristics and phenotypic plasticity, rather than to single environmental drivers (Cabuga et al., 2025).

Sex-related differences in asymmetry may reflect differences in growth trajectories, functional demands, or reproductive roles rather than solely environmental exposure. In brachyuran crabs, chelae are multifunctional structures involved in feeding, defense, and mating, and sex-specific chela morphology and use have been widely documented (Schenk & Wainwright, 2001; Hampton et al., 2014; Costa et al., 2024). Variation in asymmetry between males and females may therefore arise from sex-specific developmental pathways or energetic trade-offs, a pattern also observed in other crustacean taxa (Arundell et al., 2019).

Directional asymmetry and functional considerations. The detection of DA in certain population-sex groups suggests consistent left-right differences in chela morphology. DA in crustacean appendages has been linked to functional specialization, behavioral lateralization, or repetitive use of one appendage over the other (Schenk & Wainwright, 2001; Costa et al., 2024). In *R. ranina*, asymmetrical development could be consistent with differential use of the chelae during feeding or intraspecific interactions, but in the absence of behavioral or performance data, such interpretations remain speculative. Recently, similar functional variation in crustacean appendages has been documented using geometric morphometric approaches (Costa et al., 2024). Modern morphometric studies similarly suggest that DA in bilateral structures may occur via repeated functional loading, behavioral lateralization, or biomechanical specialization, although these processes typically require corroborative ecological or experimental evidence before causal relationships can be established (Cabuga et al., 2025).

Use of fluctuating asymmetry as a descriptive indicator. The findings of this study support the use of chela shape asymmetry as a sensitive, non-lethal morphological descriptor of developmental variation in *R. ranina*. Geometric morphometric approaches have increasingly been applied in recent years to describe shape variation and asymmetry in marine organisms, providing fine-scale resolution of morphological differences that may not be detectable with traditional linear measurements (Graham et al., 2010; Costa et al., 2024). A recent study in fishes, using Procrustes ANOVA and PCA, showed sex-linked differences in FA and highlighted the power of geometric morphometrics to detect subtle developmental variation (Cabuga et al., 2025).

Nevertheless, FA should be interpreted cautiously and in conjunction with other biological or environmental information. While elevated FA is often consistent with reduced developmental buffering, it does not provide direct evidence of specific environmental or anthropogenic stressors (Palmer & Strobeck, 1986; Graham et al., 2010). As emphasized in recent studies, asymmetry analyses are most informative when integrated with complementary data such as environmental measurements, reproductive metrics, or genetic information (Arundell et al., 2019; Costa et al., 2024).

Recent reviews have emphasized the increasing use of geometric morphometric analyses in fisheries science, as these methods offer sensitive, non-destructive means of assessing morphological variation in exploited populations. The use of Procrustes-based analyses in conjunction with multivariate visualization methods has increased the power to detect subtle developmental variation and allowed comparisons between populations in contrasting habitats (Benítez et al., 2020).

Limitations and future directions. This study is observational and does not experimentally manipulate environmental variables or directly quantify potential stressors such as pollution, fishing pressure, or food availability. In addition, the analysis focuses solely on chela morphology and does not incorporate physiological, behavioral, or genetic data that could further clarify the mechanisms underlying observed asymmetry patterns.

Future research combining geometric morphometrics with environmental monitoring, experimental exposure studies, or genetic analyses would help disentangle the relative contributions of environmental variation, functional demands, and population history to chela shape asymmetry in *R. ranina*. Longitudinal studies tracking asymmetry patterns over time would also be valuable for understanding temporal variation in developmental stability, as suggested in recent FA-based studies (Pojas & Tabugo, 2015; Hingabay, 2016). Combining geometric morphometrics, genomic analyses, physiological biomarkers, and long-term ecological datasets would provide a more complete understanding of the mechanisms underlying developmental instability in exploited crustacean populations. Such multidisciplinary approaches are increasingly encouraged in recent morphometric literature (Benítez et al., 2020; Saura et al., 2021; Costa et al., 2024). FA and sexual dimorphism of Channa striata from Agusan Marsh and Lake Mainit of Caraga Region, Philippines: A landmark-based geometric morphometric analysis (Cabuga et al., 2025).

In summary, the observed patterns of fluctuating and DA in chela morphology of *R. ranina* reflect variation in developmental stability across populations and sexes under natural conditions. While causal relationships cannot be inferred from the present data, the results contribute to a growing body of literature demonstrating the descriptive and comparative value of FA analyses in aquatic organisms (Graham et al., 2010; Ducos & Tabugo, 2015; Costa et al., 2024).

Conclusions. This study documents variation in chela shape asymmetry of the *Ranina ranina* across populations and sexes from Mindanao, Philippines, using landmark-based geometric morphometric analysis. The presence of fluctuating and DA indicates differences in developmental stability under natural conditions. It highlights the usefulness of chela morphology as a sensitive descriptor of morphological variation.

Although the observed patterns indicate population- and sex-related variation, specific causal drivers were not identified. As such, chela shape asymmetry should be interpreted as a comparative and descriptive indicator rather than as direct evidence of stressors.

Overall, the results contribute to the growing body of literature supporting the application of geometric morphometrics and FA analyses in crustaceans. When used alongside other biological and environmental information, these approaches can provide valuable insights into morphological variability in exploited marine species.

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Conflict of Interest. The authors declare no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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