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Sexual dimorphism in pill millipedes (Diplopoda)

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Abstract
Sexual size dimorphism (SSD) was investigated in the millipede genus *Sphaerotherium*. Width was extracted from Attems (1928) monograph and used to compare interspecific variation in mean volumes using a geometric morphometric approach. Based on the formula for a sphere ($4/3.\ \pi.\ r^3$), volume was calculated in seven species and an allometric coefficient of 0.7 found. The allometric equation generated for the genus was $\hat{y} = 0.00251X + 57211.22445$. Correlation between SSD and body sizes ($R = 0.749728$; $P = 0.00202$; $n=7$) does now reject Rensch's rule in *Sphaerotherium*.

Keywords: Allometry, pill millipede, Rensch's rule, *Sphaerotherium*

1. Introduction
Diplopoda are underrepresented in allometric analyses of SSD, although sexual differences are known in body mass, length, width and leg dimensions of over half the taxa studied [1-3]. Size differences occur with factors such as color, sexes, species, urbanisation and water relations [4-8]. Diplopoda resemble the majority of invertebrates where SSD is reversed [9]. SSD has consequences for the outcome of sexual encounters in diplopod mating [10-14]. The detection of a relationship between body size and SSD is known as Rensch's rule [15-16]. Rensch's rule may be explained as sexual selection [17-21]. The macro-evolutionary pattern is being resolved in the class Diplopoda [53-54].
In the present study, SSD in the genus *Sphaerotherium* was investigated. *Sphaerotherium* consists of a large number of pill millipedes with some 54-60 described tropical and subtropical species extending to the Cape Peninsula in South Africa [22-24]. Individuals of both sexes roll into a spherical ball, which is part of the mating system [25]. Rensch's rule was tested, which predicts SSD negatively correlates with mean body sizes [15].

2. Material and Methods
One factor was measured from *Sphaerotherium* species: (1) body width (mm), extracted from trusted published data [26] and intersexual comparisons performed using Wilcoxon matched pairs tests. Size was perceived as body volume and calculated based on a geometric morphometric approach using the formula for a sphere ($4/3.\ \pi.\ r^3$) where r is half the width. SSD was estimated as mean female volume divided at mean male volume and converted into a SSD index by subtracting 1 [27]. Allometry for SSD was based on an allometric model where male size = α (female size) $^{\beta}$ [28].

2.1 Statistical analysis
SSD were calculated using Microsoft Office Excel mathematical and statistical formula. Male and female widths were halved, cubed and multiplied at pi using a combination of mental arithmetic, power and product functions. Once calculated, species body volume or estimated species size was treated as the dependent y-variable or factor and measurements of mass were treated as the independent x-variables which were inserted into the Spearman's Rho online calculator (http://www.socscistatistics.com/tests/spearman/Default2.aspx). Similarly for the linear regression, volume and SSD were inserted into the online calculator for linear regression available at http://www.socscistatistics.com/tests/regression/Default.aspx. Calculations were performed and a regression was calculated and Spearman's Rho coefficients calculated at http://www.socscistatistics.com/tests/spearman/Default2.aspx. Male and female width and volume was compared for differences in magnitude using the Wilcoxon matched pairs test available at http://www.socscistatistics.com/tests/signedranks/Default.aspx.

3. Results

In 7 measurements where mean species sexual size dimorphism based on the spherical approximation (Table 1, n=7), width was larger in females than males (Z=-2.3664; W=0; N = 7; $p \leq 0.01$) and volume was significantly different between the sexes. There was a positive correlation between the log (male volume) on log (female volume) (R = 0.700557; P = 0.00526; N=7). At normal standards, the association between the two variables would be considered statistically significant. SSD ratios (female: male) for volume ranged from 0.492 – 4.359 (Mean ± SD = 1.97 ± 0.30). SSD was positively correlated with body size (R = 0.749728; P = 0.00202; n = 7). At normal standards, the association between the two variables would be considered statistically significant. The allometric equation generated for the genus was $\hat{y} = 0.00251X + 57211.22445$.

Table 1: Male and female morphometric parameters calculated in *Sphaerotherium* millipedes. Values are given as the mean measurements of sizes based on Attems' [26] widths.

Species	Male Width (mm)	Male Volume (mm^3)	Log Male Volume	Female Width (mm)	Female Volume (mm^3)	Log Female Volume
S. cinctellum	15.5	1949.816	3.290	18.6	3369.283	3.528
S. commune	6.0	113.097	2.053	9.5	448.921	2.652
S. compressum	10.75	650.65	2.813	16.5	2352.071	3.371
S. punctulatum	12	904.7787	2.957	21	4849.048	3.686
S. spinatum	11.5	796.328	2.901	15	1767.146	3.247
S. tenuitarse	7.0	179.594	2.254	8	268.083	2.428
S. tuberosum	6.75	161.031	2.207	9	381.704	2.582

Table 2: Sexual Size Dimorphism (SSD) calculated in seven species of *Sphaerotherium* pill millipedes relative to average body size (mm^3).

Species	SSD	SSD-1	Body Size (mm^3)
S. cinctellum	1.73	0.728	2659.55
S. commune	3.97	2.969	281.0089
S. compressum	3.62	2.616	1501.268
S. punctulatum	5.36	4.3594	2876.913
S. spinatum	2.21	1.219	1281.737
S. tenuitarse	1.49	0.492	223.8385
S. tuberosum	2.37	1.37	271.3673

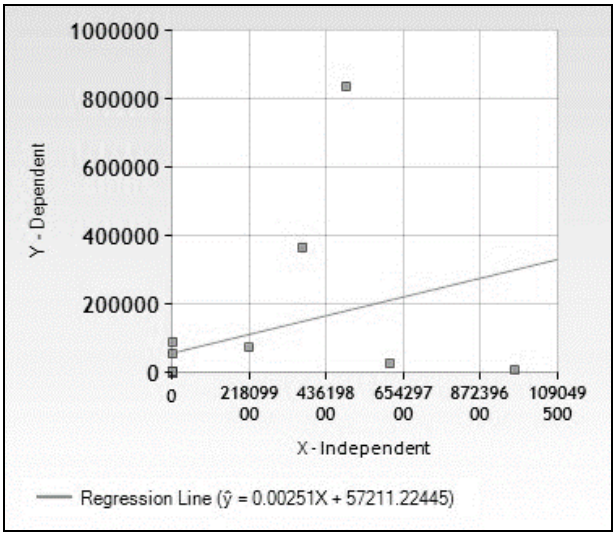

Fig 1: Regression showing the correlation between sexual size dimorphism and body size for pill millipedes (*Sphaerotherium*; N = 7)

4. Discussion

The significant difference in mean species widths, indicate selection for larger female size but does not exclude selection for male length. This could in itself be useful in assessing the contraction versus elongation hypotheses for the evolution of the millipede form [1]. The regression of SSD on body size indicates a positive correlation in *Sphaerotherium* and rejected Rensch's rule as was the pervading case for many taxa having female-biased SSD [29-53]. Mean volume ratios in *Sphaerotherium* suggest relatively high variance of SSD ranging from 1.49 in *S. tenuitarse* to 5.36 in *S. punctulatum* which were both larger than helminthomorph diplopods [54]. The inclusion of many more taxa as new species from this genus is suggested to show support the trend of larger females as seen here. The identification of species specific and intraspecific sexual size dimorphism patterns using a phylogenetic approach may provide useful information for exploring mating systems further [55]. Tree climbing behaviour suggests interspecific competition drives the SSD [56].

5. Conclusion

Rensch's rule tested and rejected in *Sphaerotherium* pill millipedes and support trends of sexual shape dimorphism with body size increases as in taxa with female-biased SSD.

6. Acknowledgements

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