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REVIEW

# Geometric morphometrics: Current and future in China

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**Abstract** Although there were many ancient Chinese mathematicians contributed a lot on geometry, Geometric morphometrics (GM) in modern concept was not firstly proposed by Chinese. The super capability of geometric morphometrics in scientific computing and problem solving has gained a lot of attentions in the world. Until early of 21 centuries, geometric morphometrics was introduced into China. Since then, GM was rapidly applied in many research fields. However, it is a pity that GM is still not well-known in China as many works are published out of China. Thus, the special issue "Geometric morphometrics: Current shape and future directions" is organized. The present issue presents a series of contributions in this scientific field. In future, there will be many considerable new developing fields on GM needed to pay more attentions, for instances, 3D geometric morphometrics, 4D analysis, visualization of amber, new machine developing, new software developing, automatic identification system, *etc*. Once these technical bottle-necks on 3D data collecting and merging geometric morphometric data from multiple characters could be solved, the automatic identification system and other fields based on Big Data would come true.

**Key words** Geometric morphometrics, 3D, LED-SIM, visualization, multiple characters.

Ancient China held leading positions in many fields in studying nature in the world (Needham & Wang, 1958). There are many notable contributors to the field of Chinese mathematics throughout the ages. For example, the oldest existent work on geometry in China comes from the philosophical Mohist canon (Mo Jing) of c. 330 BC, compiled by the followers of Mozi (470 BC-390 BC). The Mo Jing described various aspects of many fields associated with physical science and mathematics, including the definitions for geometric point, line, plane, circumference, diameter, radius, volume, *etc*. It provided an 'atomic' definition of the geometric point, stating that a line is separated into parts, and the part which has no remaining parts and thus forms the extreme end of a line is a point. Very similar to the Euclid's definitions and Plato's 'beginning of a line', the Mo Jing stated that "a point may stand at the end of a line or at its beginning like a head-presentation in childbirth." Much like the atomists of Democritus, the Mo Jing stated that a point is the smallest unit, and cannot be cut in half. It stated that two lines of equal length will always finish at the same place and also described the fact that planes without the quality of thickness (Needham & Wang, 1958; Martzloff, 1997).

Although there were many ancient Chinese mathematicians contributed a lot on geometry, Geometric morphometrics (GM) in modern concept was not firstly proposed by Chinese. Because Chinese mathematics was very concise and strongly problem based, motivated by the practical problems of the calendar, trade, land measurement, architecture, government records, taxes, *etc*. (Needham & Wang, 1958; Martzloff, 1997). Furthermore, unlike Greek mathematics there is no axiomatic development of Chinese mathematics. In this case, the calculation is more important than the geometry and other mathematical theories. For example, the most famous Chinese mathematics book of all time is the JiuZhangSuanShu (the Nine Chapters on the Mathematical Art), which is in the field of Applied Mathematics. Many Ancient Chinese mathematicians, e.g. Liu Hui (about 220–about 280), Sun Zi (about 400–about 460), Xiahou Yang (about 400–about 470),

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Zu Chongzhi (429–501), Guo Shoujing (1231–1316), *etc*., mainly contributed to this field (Needham & Wang, 1958; Martzloff, 1997).

The super capability of geometric morphometrics in scientific computing and problem solving has gained a lot of attentions in the world. Many notable books, papers, and software were published on this field and shaped the current framework of GM (Adam *et al*., 2013; Friedrich *et al*., 2013; Bai *et al*., 2014b; Bai & Yang, 2014). Until early of 21 centuries, geometric morphometrics was introduced into China. Since then, GM was rapidly applied in many research fields, especially after several GM workshops in Beijing by Dr. Klingenberg, Dr. Ming Bai, *etc*. Several reviews (e.g. Bai & Yang, 2007, 2014; Ge *et al*., 2012; Bai *et al*., 2014b), book chapter (Bai, 2014) and research articles (Bai *et al*., 2010, 2011, 2012, 2014a, 2015; Chesters *et al*., 2012; Song *et al*., 2014; Li *et al*., 2016) by Chinese were came out afterward.

However, it is a pity that GM is still not well-known in China as many works are published out of China. Thus, the journal, *Zoological Systematics*, invited the author organizing a special issue "Geometric morphometrics: Current shape and future directions" to introduce geometric morphometrics. The present issue presents a series of contributions in this scientific field. For example, a very comprehensive review on the history, development methods and prospects of morphometrics was presented by Prof. Norman MacLeod (2017). Two method papers were included, firstly is a web based tool to merge geometric morphometric data from multiple characters and demonstrated by an example from dung beetles were developed by Bai *et al.* (2017). Second method paper is on the maximum likelihood identification method applied to insect morphometric data (Dujardin *et al*., 2017). Six research articles on different groups (beetles, bugs, shell, birds and human) using different GM approaches were conducted.

In future, there will be many considerable new developing fields on GM needed to pay more attentions, for instances, 3D geometric morphometrics (Bai *et al*., 2014b), 4D analysis, visualization of amber (Bai *et al*., 2016; Oliveira *et al*., 2016; Xing *et al*., 2016a, b), new machine developing (Ruan *et al*., 2016), new software developing (Bai *et al*., 2017), automatic identification system, *etc*. Especially the situations on the high expenses and low efficiency on 3D data collecting will be greatly changed with the applications of new developed machine, LED-SIM, which can be highly effective and may provide high quality 3D images for zoological studies (Ruan *et al*., 2016). For example, the finest XY-plane resolution of LED-SIM could approach 90 nm with a 100× objective lens and the imaging speed of a complete stack of images (for 3D representation) ranged from tens of seconds to a few minutes, which was dependent on the resolution and the number of frames required (Table 1). Once these technical bottle-necks on 3D data collecting (Ruan *et al*., 2016) and merging geometric morphometric data from multiple characters (Bai *et al*., 2017) could be solved, the automatic identification system and other fields based on Big Data would come true.

**Table 1. Comparison of the features of different major 3D imaging systems used in zoological studies. The features of the different methods are based on our knowledge of the different pieces of equipment established by our previous studies; various statistics from recent papers are also referenced (from Ruan *et al.*, 2016).**

| | Lateral resolution | Suitable sample type | Estimated cost (US$) | Suitable sample size | Imaging light source | Sample preparation | Imaging time | Imaging color |
|---|---|---|---|---|---|---|---|---|
| LED-SIM | 0.1 μm | Dry or wet | ~200,000 | <10 mm | LED | Fast | <10 min | Pseudo color |
| Laser-SIM | 0.1 μm | Dry or wet | 550,000–650,000 | <10 mm | Laser | Fast | <10 min | Pseudo color |
| CLSM | 0.2 μm | Dry or wet | 500,000–700,000 | <10 mm | Laser | Medium | 30 min–1 h | Pseudo color |
| SPIM | 0.2 μm | Dry or wet | 300,000–500,000 | <10 mm | Laser | Medium | <10 min | Pseudo color |
| Micro-CT | 0.5–5 μm | Dry or wet | 500,000–700,000 | 1–200 mm | X-ray | Medium | 2–24 h | Black and white |
| FIB/SBF-SEM | 4–7 nm | Dry | 800,000–900,000 | <1 mm | Electron and ion beam | Medium | 8–9 h | Black and white |
| MRI | 20 μm | Wet | 600,000–800,000 | 10–50 mm | Radio frequency | Medium | ~24 h | Pseudo color |

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