Automatic generation of objective footprint outlines (#33978)

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Automatic generation of objective footprint outlines

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The objective definition of footprint margins poses a central problem in ichnology. The transition from the footprint to the surrounding sediment is often continuous, and the footprint wall complex, requiring interpolation, approximation, and a priori assumptions about trackmaker anatomy to arrive at feasible interpretations of footprint shapes. The degree of subjectivity of such interpretations is substantial, and outlines produced by separate researchers can differ greatly. As a consequence, statistical shape analysis, regardless if based on linear and angular measurements or on the shape as a whole, are neither fully repeatable nor objective.

Here I present an algorithm implemented in the programming environment R that is able to generate continuous footprint outlines based on three-dimensional models—fully automatically, objectively, and repeatable. The approach, which is based on contour lines extracted from the model, traces the outline at the point where the slope of the track wall is steepest. The resulting outlines tend to correspond well with human-made interpretative drawings regarding the overall shape, although faint anatomical details are not always recorded. While not suited as a full replacement of interpretative drawings in many cases, these objective outlines allow for ~~fully~~ objective quantitative analyses of footprint shapes.

Automatic generation of objective footprint outlines

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Abstract

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Introduction

Fossil footprints are an important supplement to the body fossil record, given their abundance and nature as life traces that directly record behaviour and locomotion. Yet, the potential of analyses combining footprint and body fossil data is not yet exhausted, partly due to the slow advancement of objective and quantitative methodology in ichnology. A central problem in applying such methods to footprint data is the inability to objectively define the margins of a footprint, especially when the footprint indistinctly grades into the surrounding sediment.

Falkingham (2016) showed that the length of a footprint can vary as much as 27% depending on the height level chosen for measurement. Various criteria for the identification of the footprint margin have been proposed, including the point of inflexion of the footprint wall, the minimum outline, and the selection of a single contour line, amongst others (Falkingham, 2016). However, none of these criteria is unambiguously applicable to a wider range of different footprints, which typically show multiple inflexion points and often do not show distinct minimum outlines (Falkingham, 2016; Lallensack, van Heteren & Wings, 2016). Adding to the problem, the vast majority of ichnological publications does not specify the criteria used for defining the footprint margins. The inability to objectively define footprint margins is highly problematic especially when quantitative methods are to be applied to analyse footprint shape, since such analyses can only generate fully objective results when based on objective input data (Falkingham, 2016).

The problem persists when not only linear and angular measurements but a single, two-dimensional outline abstracting the whole shape of the footprint is to be extracted. The outlines of one and the same footprint, when drawn by separate researchers, can differ considerably from each other (Thulborn, 1990), which repeatedly led to calls for caution in interpreting such data (e.g., Sarjeant, 1975; Thulborn, 1990; Falkingham, 2010, 2016). Furthermore, the high degree of simplification of two-dimensional outlines has been criticised, proposing that the full three-dimensional profile should be retained instead (e.g., Ishigaki & Fujisaki, 1989; Belvedere et al., 2018). Nevertheless, outline drawings remain the most widely used means for distributing footprint shape data, also because most anatomical information of the footprint is contained in its outline. Problematically, it is often not possible or desirable to excavate and archive footprints in museum collections, which is why material is often difficult to access or get degraded by weathering (Bennett et al., 2013). Ichnologists, therefore, are in many cases forced to rely on subjective outline drawings presented in the literature for ichnotaxonomic attributions and comparisons with relevant material.

Recent efforts to increase objectivity in footprint research rely on 3D-digitization techniques, most importantly photogrammetry, which allows for the fast and cost-effective capturing of footprint morphologies in high resolution (e.g., Falkingham, 2012; Mallison & Wings, 2014; Matthews, Noble & Breithaupt, 2016). A relatively new set of methods in the field, these techniques promise to solve critical problems of collection and dissemination of footprint data, and have been recently accepted as best practice in the documentation of fossil footprints (Falkingham et al., 2018). Thus, the availability of such models can be expected to increase greatly in the future.

Although a number of methods for the analysis of footprint shapes exist, none can effectively solve or circumvent the problem of the definition of footprint margins. Comparative approaches using 3D geometric morphometrics (Bennett et al., 2016; e.g., Belvedere et al., 2018) will include both the footprint and the surrounding sediment unless the footprint margin has been defined a priori. Therefore, such methods are feasible only when foot posture, most importantly the interdigital angles, is constant, as otherwise regions of the footprint may get averaged with surrounding sediment. Furthermore, the registration of the separate footprints still requires user-defined landmarks, which usually cannot be placed unequivocally in the absence of an objective definition of the footprint margin.

The algorithm presented herein allows for the fully objective and automatic generation of continuous outlines based on 3D surface models of footprints. The method relies on the steepness of the footprint slope (i.e., the inflexion point of the footprint wall), the probably most commonly used criterium for the definition of footprint margins (Ishigaki & Fujisaki, 1989).

Methods

The algorithm presented herein, implemented in the programming environment R, allows for the fully objective and automatic generation of continuous outlines based on 3D surface models of footprints. Many required functions have been already implemented in the wealth of packages available for R; these were used whenever possible, reducing the script to approximately 650 lines of code. The implemented R function, named “oboutline”, will perform the import of the 3D model, calculation of the outline, and export of graphics automatically in a single step, without requiring additional human input.

Model import, orientation, and contour line generation

Import of 3D-models is achieved using the vcgImport function of the Rvcg package (Schlager, 2017), which supports commonly used formats including the widely used PLY. The supplied 3D-model should contain only a single complete footprint as well as a margin of surrounding surface. The exact extent of the surrounding margin will not alter results except when an increased margin size includes additional large-scale continuous contours that enclose the footprint. After import, the script rotates the point cloud of the extracted vertex point xyz-coordinates to fit the horizontal plane (i.e., the tracking surface on which the animal walked) by employing principal component analysis (PCA) on the three variables (x,y,z). The PCA fits three orthogonal axes (PC1–3) to the point cloud, with PC1 defined as the axis with the greatest variation, followed by PC2 and PC3. In most situations, PC1 and PC2 will represent the horizontal plane (the plane of greatest variation), and PC3 the relief (i.e., the deviation from the horizontal plane). Problematically, the point cloud can get mirror-inverted during PCA fitting as the signs of the columns of the rotation matrix are arbitrary, a problem also occurring in respective implementations in 3D-mesh software like Meshlab (tested with version v2016.12) or CloudCompare (tested with version 2.9). The present function calculates the Procrustes distance (a measure of shape difference) of a subset of points of the model before and after the PCA fit, and will mirror back when detecting a significant difference.

All subsequent computations are based on contour lines of 30 equally spaced height levels extracted from the point cloud using the “getContourLines” function of the contoureR R package

(Hamilton, 2015, Fig. 1B). Contour lines reduce the complex three-dimensional problem to a simpler and easier-to-handle two-dimensional one, and form the natural basis for 2D footprint outlines. Before the objective outline can be extracted, a number of additional steps are required, including 1) the removal of contours not representative for the footprint wall and 2) the establishment of homology between the points of separate contours.

Contours not representative for the footprint wall are excluded based on simple criteria. First, all open contours are removed, eliminating structures that continue beyond the margins of the model. Second, only the longest contour of each height level is selected and kept, respectively, with all others removed. This results in a stack of continuous contours, with one contour per height level. Third, all contours less than 50% of the length of the longest contour are removed, while assuring that no gaps within the stack are being created. This approach eliminates smaller structures within the footprint that are unlikely to contain relevant information on the footprint wall (Fig. 1C). The resulting stack of contours may still include a number of contours that convey little or no information on the footprint wall, including roundish contours around the actual footprint. To eliminate these contours as well, a more complex approach is employed involving the homologization of contours (as described below) and calculation of Procrustes distances to quantify the shape differences between individual contours. Starting from the middle contour of the stack, the Procrustes distances of each contour with its next lowest (or highest) neighbour are compared; if the Procrustes distance between two contours exceeds a pre-defined threshold-value, the upper (or lower) of this contour and all following contours are removed (Fig. 1D).

Homologization of contours

Even if the starting point would correspond between all contours and if each contour would contain an equal number of equidistant points (requirements not fulfilled a priori), the individual points of the separate contours would tend to deviate from each other when far from the starting point, as the shapes of the contours are not identical. Because of this reason, when producing a simple mean shape, points will be averaged obliquely rather than perpendicularly to the footprint wall, leading to erroneous results. The implemented solution detects a number of "bottlenecks"—pairs of points with minimum distance between the inner and outer contour. Points forming the bottleneck will be considered homologous (define a line that is assumed to be perpendicular to the footprint wall), and the points in-between the bottlenecks will be interpolated by resampling.

First, all contours are resampled to the same number of equidistant points, using a number of n=500 points per default. The resulting contours can be variously oriented clockwise or counter-clockwise; contours are reversed accordingly to achieve uniform orientations. Second, Euclidean distances between all possible pairs of the inner and outer contour of the stack are calculated and stored in a matrix with the dimensions n x n. The pair with the minimum distance, the first bottleneck, is then extracted, and those points of the intermediate contours are detected that are closest to a line defined by the bottleneck points. The resulting set of homologous points is then defined as the starting point of the contours. Third, additional bottlenecks are detected to establish homology. The implemented algorithm first detects a second bottleneck on the side of the footprint opposite to the first bottleneck; two additional bottlenecks are then found on each side between the first and second bottleneck. More bottlenecks are detected within the intermediate sections if the latter are long enough. In all cases, bottlenecks in proximity to existing bottlenecks are prevented, assuring a roughly equal distribution of bottlenecks along the outline (Fig. 1D). Finally, the individual sections between the bottlenecks are resampled to equal numbers of equidistant points, which can now be considered homologous.

Tracing of the steepest slope

The objective outline will be traced along the steepest slope of the track wall. For each point within each set of homologous points, the minimum distance between the neighbouring contours is measured. A set of homologous points is not always fully perpendicular to the footprint wall, especially when the section between the bottleneck points is long and contours differ much in orientation. For this reason, the algorithm does not simply compute the distances within the set of homologous points, but the distances between each of the homologous points and all nearby points within and outside of the set. The steepest slope computed this way is seldom continuous along the whole outline, but rather tends to fade out and continue on a different height level, frequently leading to abrupt steps in the outline that are obviously incompatible with human interpretations. For this reason, the algorithm does not only detect the steepest point, but takes into account the steepness of all other points. Then, the final coordinate of the steepest slope is computed as the weighted arithmetic mean of all these points. Points will receive equal weight only when the steepness is equal; the lower the steepness compared to the steepest slope, the less weight is given.

The continuous and smooth final outline is produced by applying an approximating function to the resulting set of points. Of various tested options, including B-splines and Bézier curves, elliptic Fourier transforms were found to produce results most similar to those expected from a human interpreter (Fig. 1F, 2). Elliptic Fourier transforms are performed using the "efourier" function of the R package Momocs (Bonhomme et al., 2014) using 25 harmonics and 10 smoothing iterations.

As the resulting objective outline and contour stack will be rotated arbitrarily, an algorithm attempts to rotate both outline and stack into an upright orientation. In a first step, the circular mean of the angles between all points of the objective outline is computed, and the shape rotated by this mean angle. In elongated shapes, the resulting mean orientation can be assumed to approximate the orientation of the long axis of the shape. In a second step, it is determined whether the shapes have to be rotated by 180° to have the digital impressions facing upwards.

Discussion

Human-made interpretational footprint drawings aim to capture as much information of trackmaker anatomy as possible. Although slope steepness is the most important criterion, the steepest slope will frequently fade out along the footprint wall to continue at a different height level, making interpolation unavoidable. Furthermore, humans tend to make a priori assumptions about trackmaker anatomy when producing the outlines, which allows them to exclude extramorphological (unrelated to the foot anatomy) features and emphasize anatomical features of interest such as digital pad impressions and claw marks.

The present algorithm is successful in detecting and interpolating outlines even when the steepest parts of the slope are indistinct (Fig. 2). It does currently not include any a priori assumptions, which keeps the algorithm simple and predictable, and applicable to a wide range of footprint types. In the absence of such assumptions, however, the outlines expectedly tend to provide less information on the presumed foot anatomy than interpretative drawings. Furthermore, a correct alignment of a set of shapes (i.e., the removal of differences in size, translation, and rotation), a prerequisite for quantitative shape analysis, is not possible without a priori assumptions on anatomy. Other current limitations of the presented software include the prerequisite that the footprint has to be continuous (i.e., outlines have to describe the whole impression), and that only information within the set of selected continuous outlines is taken into account. The mentioned problems are planned to be resolved in future versions of the script.

The presented approach is demonstrated on six fossil footprints previously published in the literature (Fig. 2). All examples were processed using the same script version and parameters. 3D models used to produce Fig. 1 and Fig. 2A–C are available in the electronic supplementary material, while the model for Fig. 2F is available from Bennett (2013). Five of these examples (Fig. 2A–E) are compared with published interpretative drawings that had been produced using the same 3D-models. Footprints T3/47, T3/37, and I1-35 (Fig. 2A–C, respectively) come from the Lower Cretaceous of Münchehagen, Germany (Lallensack, van Heteren & Wings, 2016; Wings, Lallensack & Mallison, 2016). All three footprints were left by the right foot. T3/47 and T3/37 were part of a larger theropod and I1/35 (Fig. 2C) of an ornithopod trackway, both showing a pronounced intratrackway variability. The objective outlines (red continuous lines) are generally in accordance with published interpretational drawings (dotted blue lines). However, the sediment bars between the digital impressions tend to be less extensive, and digital impression IV in T3/47 is abbreviated in the objective outline due to sediment infilling of the distal tip of the impression.

Tracks 5 and 6 of QM F10322 (Fig. 2D–E) are the left and right pedal impressions of a large tridactyl trackway from the Upper Cretaceous of Lark Quarry in Queensland, Australia (Thulborn & Wade, 1984; Romilio & Salisbury, 2011, 2014). The 3D-models, based on photographs of the *in situ* specimen taken in 2013, were provided by Anthony Romilio. The trackway became famous after it was suggested to have been left by a large theropod causing a dinosaur stampede (Thulborn & Wade, 1984), a hypothesis that has been discussed controversially in recent years (Romilio & Salisbury, 2011, 2014; Thulborn, 2013, 2017; Romilio, Tucker & Salisbury, 2013), with the identification of the large tridactyl trackmaker as either a theropod or an ornithopod constituting a major point of disagreement. This discussion is instructive in showing how much interpretative outlines can differ when produced by separate researchers with different preconceptions about the responsible trackmaker taxon. Well aware of the subjectivity problem, Romilio & Salisbury (2014, fig. 7F, 8F) did not produce traditional outline drawings but selected a single contour line they considered representative. Still, this approach is not completely objective, as separate contours can differ greatly in shape and dimensions (Falkingham, 2016). The calculated outlines presented herein correspond well with those of Romilio & Salisbury (2014) (Fig. 2D–E). However, they differ considerably from outlines of the same imprints presented by Thulborn & Wade (1984, plate 17), and especially from a more recent interpretation of track 5 by Thulborn (2017, fig. 5 (3)). The sixth example presented herein, a hominin footprint from the famous Laetoli tracksite of Tanzania (Leakey & Hay (1979); data from Bennett (2013)), demonstrates that the present approach is equally well applicable to non-dinosaurian footprints.

Conclusions

The lack of widely applicable, objective means for defining the footprint margin is among the most vexing problems in the research of fossil footprints. The present algorithm automatically generates continuous objective footprint outlines by employing the criterium of the steepest slope. Although these outlines tend to correspond with human interpretations, extramorphological features unrelated to the foot anatomy may be incorporated, and anatomical detail not captured by the steepest slope may be excluded. While not a fully appropriate replacement for human-made drawings in most cases, computed outlines may be used as an objective basis for the production of interpretational drawings, reducing interpretational bias. Most importantly, the approach paves the way for fully objective analyses of footprint shape.

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Figure 1

Procedure of calculating objective outlines of footprints using ornithopod footprint I1-31 from the Lower Cretaceous of Münchehagen, Germany as example

(**A)** The xyz point cloud is extracted and fitted to the horizontal plane. (**B)** Contour lines for 30 height levels are extracted based. (**C)** Incomplete and short contours are removed. (**D)** Further contours are removed based on Procrustes distances (i.e., shape similarities), and bottleneck points determined in order to establish correspondence between outlines (red points). (**E)** The location of the steepest slope is computed. (**F)** Fitting of an approximating, smooth curve using Elliptical Fourier transforms. Axes scales are in metres, and all plots are in z-direction (top view).

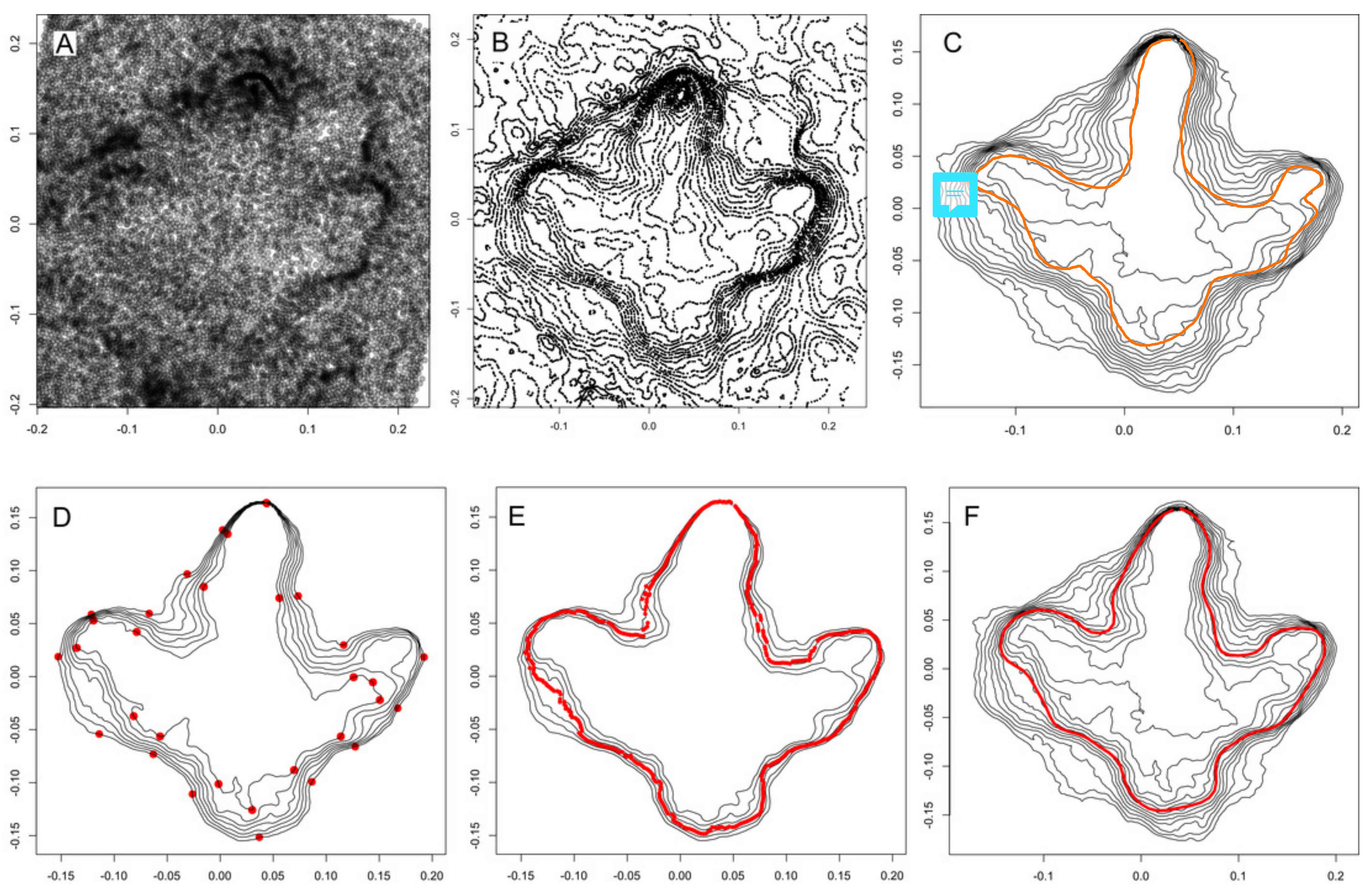

Figure 2

Examples of calculated objective outlines

Objective outlines calculated for various footprints (continuous red lines), with published interpretational drawings (dotted blue lines; not available for C) for comparison. (**A–C)** Footprints of theropod trackway T3 (A: T3/47; B: T3/37) and ornithopod trackway I1 (I1/35) from the Lower Cretaceous Münchehagen locality, Germany. (**C–D)** Footprints of a large tridactyl trackmaker (specimen QM F10322) from the Upper Cretaceous of Lark Quarry, Australia (C: L3; D: R3). 3D-model were provided by Anthony Romilio. (**E)** Hominin footprint G1-33 from the Pliocene of Laetoli, Tanzania.