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A three-dimensional geometric morphometric study of the effects of erosion on the morphologies of modern and prehistoric footprints☆

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A R T I C L E I N F O

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A B S T R A C T

Introduction: Fossilised footprints have been discovered all over the world and can provide information regarding the foot size and subsequent body size estimates of the track makers or an insight into the kinematics of the foot/lower limb. After exposure, these fossils rapidly erode. It is predicted that footprint morphology is compromised after creation, prior to fossilisation and that erosion after exposure will affect the morphology of a footprint after exposure. To date, no studies have assessed if degradation prior to fossilisation and/or after fossilisation, and subsequent exposure, affects the morphology of the print, thereby affecting any measurements taken. This study aims to quantify these pre- and post-erosional processes.
Materials and methods: A set of experimentally generated footprints were created to test the effects of degradation of footprint morphology prior to fossilisation. In addition, Holocene footprints were recorded at Formby Point, Sefton, UK. In just over a week tidal action had completely eroded the Holocene beds. Photogrammetry was applied to the experimental human footprints and a selection of Holocene human and animal footprints. Three-dimensional Geometric Morphometric methods were utilised to estimate differences in shape and size.
Results: Results from the experimental footprints indicate that weather action affects the size and shape of a footprint prior to fossilisation. When the weather was dry, footprint shape and size showed little difference for two weeks, but rainfall caused significant changes. The Holocene footprints show that after fossilisation and exposure to coastal erosion, footprint rigidity is highly compromised. The human footprint borders progressively recede, increasing length and width each day. Footprint depth, often used to inform upon speed and kinematics, varied considerably in one week. Some regions becoming shallower, others increasing in depth. Similar results were found for the animal footprints, but with less significant changes in shape and size determined.
Conclusion: Observed significant differences in measurements result in problems for predicting stature, mass, sex, and kinematic analyses. This warrants caution when making interpretations from fossilised footprints. Rapid recording of fossilised prints from first exposure and assessing pre-fossilisation processed are necessities when recording footprint surfaces.

1. Introduction

Fossilised hominin footprint localities have been discovered across Africa, Eurasia, Australia and the Americas (Leakey and Hay, 1979; Behrensmeyer and Laporte, 1981; Roberts and Berger, 1997; Mietto et al., 2003; Watson et al., 2005; Webb, 2007; Bennett et al., 2009; Roberts, 2009; Morse et al., 2013; Felstead et al., 2014; Ashton et al., 2014; Masao et al., 2016). In lieu of skeletal material, fossil footprints can be used to infer body dimensions of the track makers (Bennett and Morse, 2014). Numerous fossil and forensic-based studies have been conducted that have attempted to find a correlation between footprint measurements (e.g.; forefoot breadth, heel breadth, length, toe extremity length, etc.) and body dimensions, such as stature, body mass, hip height, sex and age (Krishan, 2006; Kanchan et al., 2008; Avanzini et al., 2008; Bennett et al., 2009; Dingwall et al., 2013; Domjanic et al., 2015; Hatala et al., 2016a).

For example, stature is often predicted using the length of the foot by applying Martin's ratio of 0.15 (Martin, 1914). Dependant on substrate material properties, these measurements extracted from a single trackway belonging to a single individual can vary substantially. Stature and mass predictions from just one trackway from Walvis Bay, Namibia have estimated that the individual ranged from 1.35 m to

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1.73 m tall, with the individual being either malnourished or clinically obese (Bennett and Morse, 2014). Evidently, slight variations in a trackway results in grossly variable biometric predictions.

In other locations, such as at Laetoli, Tanzania and Ileret, Kenya, the substrate material properties are much more uniform across a trackway, and biometric data that is extracted is much less variable (Bennett et al., 2009). Less variable measurements have resulted in numerous studies utilising these measurements to predict not only biometric data, but also kinematic data (Schmid, 2004; Berge et al., 2006; Vaughan and Blaszczyk, 2008; Raichlen et al., 2008; Raichlen et al., 2010; Crompton et al., 2011; Bates et al., 2013; Dingwall et al., 2013; Bennett et al., 2016; Hatala et al., 2016b; Masao et al., 2016; Raichlen and Gordon, 2017). These studies have allowed palaeoanthropologists to assess evolutionary trends in bipedal locomotion and body proportions.

It has been previously demonstrated that footprints are susceptible to taphonomic changes prior to diagenesis as the result of a number of variables; weather conditions, changes in surface hydrology or bioturbation (Marty et al., 2009; Bennett and Morse, 2014). After the footprints have undergone diagenesis, and have either become exposed or excavated a number of variables can lead to the footprints becoming eroded, thus affecting footprint shape (Bennett et al., 2013). As with any archaeological material, once the fossils are uncovered and exposed to the elements they will begin to erode, with softer, lithified sediments being more susceptible to erosion (Bennett et al., 2013). It must be acknowledged that weather action, such as wind or rain, may affect the size and shape of a footprint in a similar manner that slight variations in substrate typology may affect a footprint (Marty et al., 2009; Bennett et al., 2013).

No studies to date have quantified the effects of degradation on morphology, and how this can affect measurements taken from a footprint. The current study aims to quantitatively assess the effects of taphonomy and erosion on footprint morphology through the assessment of experimental and Holocene footprints. New discoveries of human trackways at Formby Point, Merseyside has offered a unique opportunity to record a set of Holocene footprints as they rapidly eroded.

This study proposes that footprints are at risk of significant morphological change which will alter body size predictions at two stages. The first stage is immediately after footprint creation. The second stage is post-excavation. It is predicted that a delay in events leading to excavation and recording could result in changes in shape and size of a footprints, particularly in easily deformable softer sediments that are more susceptible to morphological changes (Bennett et al., 2006).

We use a selection of experimentally generated footprints to assess changes in footprint morphology prior to fossilisation. Holocene human and animal footprints discovered along the Sefton Coast were also assessed to determine if there is any changes in shape or size per day after exposure. It is predicted that the longer a footprint is exposed then there will be a significant change in shape and size of the print. Shape change is predicted to affect measurements of the foot used to inform upon body size estimates. An improvement on understanding the effects of erosion on morphology will improve the ability to accurately assess body size estimates from future footprint sites.

1.1. Geological and archaeological context

Formby Point is located along the Sefton Coast in Merseyside, England and is characterised by silty, fine-grained sands and peat sediments, and sand dunes (Roberts et al., 1996) preserved in unlithified, soft-sediments (Roberts, 2009; Bennett and Morse, 2014). Encroaching coastlines have led to the exposure of numerous ancient sediments since the 1970s, many of which contain over 145 Holocene human trackways and animal footprints along a 4 km stretch of this coastline (Huddart et al., 1999; Roberts, 2009). The Formby Point sediments are similar to other fossilised sediment beds at Terra Amata, a site containing a Neanderthal footprints (De Lumley, 1966).

Carbon and optically stimulated luminescence (OSL) dating of the previously excavated sediments have yielded dates from 6650 ± 700 OSL BP ~3575 ± 45 ^{14}C BP (Roberts, 2009). The latter date was obtained by dating roots that overlay the Holocene beds, indicating a *terminus ante quem* for the beds (Roberts et al., 1996; Huddart et al., 1999; Roberts, 2009), confirming a Mesolithic age. These beds offer an interesting insight into human activity of the Late Mesolithic-Early Neolithic transition along the Sefton Coast.

In June 2016 three human trackways were exposed due to wave erosion at Formby Point immersed in over 700 animal footprints. Auroch, roe and red deer, crane bird, wolf/dog, and beaver footprints have been identified (Roberts et al., 1996; A. Burns 2017, pers. comm.). The interaction of many animal and human prints offer a glimpse into Mesolithic human activity, and even offer a unique opportunity to assess the gait dynamics of an extinct species of cattle, although this is not the focus of the current study.

The Holocene sediment layer was excavated by staff and students of The University of Manchester. Unfortunately, the bed was destroyed in just under two weeks after exposure due to the destructive nature of the high tide. Twice a day the sediment layer was completely immersed by high tide, with the prints only reappearing with low tide. Visually, it was possible to see the daily erosion of the footprints as the direct result of wave action (Fig. 1). The sediment bed was unlithified and despite efforts to prevent human and animal interference with the footprints, tidal action still led to the destruction of the footprint bed quite rapidly due to the bed being composed of soft, easily deformable silts. Such a rapid degradation of the footprints that was noticeable by the naked eye is hypothesised to have resulted in significant morphological change. Importantly, we expect that linear measurements of the foot will have changed on a daily basis. As previously discussed, these linear measurements are used to predict an individual's biometric information. Changes in these measurements are expected to produce highly variable predictions regarding body size estimations.

Holocene footprints have previously been exposed along the Sefton Coast (Roberts, 2009), with fossilised footprints appearing at other coastal sites in the UK, such as at Happisburgh, Suffolk (Ashton et al., 2014). These beds containing unlithified footprints were also destroyed rapidly due to tidal action in a matter of weeks. If our study is successful in determining that morphological changes are paramount in coastal locations, particularly with footprints that are unlithified, then the biometric data that has been previously published from these sites, such as at Happisburgh (Ashton et al., 2014), is questionable. The sediments are variable between Formby Point and Happisburgh, but it is a fair assumption that two soft, unlithified sediment beds would have reacted similarly when exposed to the same variables: vigorous tidal action and poor weather conditions. Both of these beds deformed and were destroyed rapidly. It is expected that both sites also experienced changes in footprint morphology coinciding with the rapid destruction of the beds.

The rapid erosion of the footprints at Formby Point have offered a unique opportunity to quantitatively assess the effects of daily degradation on footprint morphology. If the current study is successful in determining that footprints undergo daily morphological changes, then our results will have considerable implications for future studies that assess footprint discoveries from coastal locations.

2. Materials

2.1. Experimental set-up

A selection of experimental footprints were created in homogenous fine-grained sand composed of rounded to sub-angular particles measuring ~0.06–0.7 mm in diameter with ~20% saturation at a 40 mm depth (Fig. 2). Previous experiments have determined that this is the optimal saturation for footprint definition, whereby sand composition has no significant effect on morphology after saturation (D'Août et al.,