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One size fits all? Stature estimation from footprints and the effect of substrate and speed on footprint creation

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Abstract

Estimation of stature from footprint lengths is a common prediction in forensic cases and in paleoanthropology upon the discovery of fossil footprints. Many studies, which have estimated stature from footprints, generally use a "one-size-fits-all" approach that usually involves applying a known ratio of foot length to total stature to do so, although this method has fallen out of practice in forensic cases in recent years but is still commonly used for fossil trace evidence. Yet, we know that substrate and speed can change the dimensions of a footprint, so why are these "one-size-fits-all" approaches still used today? We tested footprint production across different substrates at a walk, a fast walk, and a jog. We calculated how accurately footprint dimensions were impressed between these different conditions and identified sources of error in footprint lengths, and the percentage changes of how significantly a footprint can change in length between different conditions. We provide a table with different ratios that we encourage practitioners/field scientists to refer to and use when estimating stature from footprints, with respect to the substrate on which the footprint was created and the speed at which it was created. We actively encourage researchers to add the ratios by testing more substrates so that in the future stature can be more accurately estimated, thus aiding the paleoanthropological community, but also forensic investigations by statistically highlighting how different conditions can affect trace dimensions.

KEYWORDS
footprints, ichnology, stature

1 | INTRODUCTION

The estimation of stature from the human foot/footprints has been extensively researched in the last 20 years (Abledu et al., 2015; Asadujjaman et al., 2020; Domjanic et al., 2015; Hemy et al., 2013; Kanchan et al., 2013, 2014; Krishan, 2007; Krishan et al., 2015; Reel et al., 2010). Being able to predict a person's stature from the impression of their foot (a footprint) is an important research area in forensic science (Agnihotri et al., 2007; Barker & Scheuer, 1998; Kanchan et al., 2012; Krishan, 2008) and has also been informative for predicting the height of early humans from fossil footprints (Domjanic et al., 2015; Ashton et al., 2014; Atamturk, 2010; Bennett et al., 2009, 2020; Crompton et al., 2012; Dingwall et al., 2013; Wiseman et al., 2020). Numerous studies have investigated the relationship between stature and footprint

[The copyright line for this article was changed on 18th December 2021 after original online publication] dimensions, usually focusing on specific populations to identify the optimal methods for stature predictions from a certain region (Asadujjaman et al., 2020). Others have attempted to refine stature prediction methods to produce the most accurate representation of a person's height using a "global" method—that is, "one-size-fits-all" approach (Martin, 1914; Robbins, 1985).

The ratio of foot length to total body height is one such method to predict the track-maker's stature (Martin, 1914; Robbins, 1985; Sen & Ghosh, 2008) and is generally the most popular method of stature prediction, particularly in paleoichnology (Dingwall et al., 2013). Stature is often predicted from fossil footprints by assuming that total print length is either 15% of stature for unshod individuals (Martin, 1914) or 14% of stature for shod individuals (Robbins, 1985), although this method has been discredited in some forensic cases (Krishan et al., 2015). While in theory this method works by providing a relative prediction, in practice the method needs refinement. There are numerous factors that can affect the size and shape of a footprint which need to be brought into consideration when making stature predictions. For example, print length within a trackway belonging to a single individual can vary substantially when the underlying substrate materials are changed (Milan & Bromley, 2006; Morse et al., 2013). Changes in hydrology, particle size, and even particle composition can all influence the resultant footprint (Belvedere et al., 2021; Bennett & Morse, 2014; Wiseman & De Groote, 2018). Stature predictions from just one fossil trackway from Walvis Bay, Namibia have estimated that the individual ranged from 1.35 to 1.73 m tall, with the individual claimed to be either malnourished or clinically obese (Bennett & Morse, 2014; Morse et al., 2013). Evidently, slight variations within a trackway results in grossly variable biometric predictions and this must be investigated. Generally speaking, the error in extracting accurate dimensions from a track increases for those produced on deeper and less compliant substrates due to sediment instability around track borders (Milan & Bromley, 2006; Gatesy & Falkingham, 2017). Consequently, extracting biometric information from deep tracks is problematic owing to a poor relationship between track shape with foot shape (Gatesy & Falkingham, 2017; Hatala et al., 2018). This problem extends to changes in speed. If the speed of the track-maker increases, then so does the resultant footprint dimensions (Bennett & Morse, 2014).

Yet, numerous studies still use the generic 14% or 15% ratios to predict stature from footprint length, especially in fossil footprints despite many of these footprints having been formed in a range of substrates, from natrocarbonite ash at Laetoli, Tanzania (Leakey & Harris, 1987) to sandy silts at Formby Point, UK (Wiseman & De Groote, 2018). It is appropriate to ask the question: are we overestimating or underestimating stature in these fossil hominins—and perhaps even in forensic cases—by using the wrong ratio/prediction method? Here, we experimentally tested footprint production in two different substrates of varying hydrology at three different speeds to determine if (1) footprint dimensions were variable between each of these conditions, and (2) if a specific ratio should be used for each condition (i.e., perhaps a shorter ratio may be more appropriate for footprints created on softer substrates at faster speeds versus that of a firm substrate at slower speeds). Importantly, we test footprint creation here to highlight how footprints are easily changeable across a range of conditions.

2 | METHODS AND MATERIALS

All data were recorded in the Biomechanics Laboratory in the Tom Reilly Building, Liverpool John Moores University, UK. Ethical approval was granted by the Liverpool John Moores University Research Ethics Committee (REC: 16/NSP/041). Adult participants (19–40 years old) that were free from current lower limb or spinal pathologies who were able to move unassisted were recruited for this study. This resulted in 55 males and 45 females volunteering to be a participant in the trials. Participants were selected with the aim to maximize variation in ethnicity and body mass (Figure 1). Biometric information of each participant was recorded. This included measuring each participant's height, weight, foot length (left and right using an osteometric foot board), biological sex, and date of birth.

2.1 | Experimental design

Two trackways measuring 12 m long by 0.6 m wide were constructed that were filled with finegrained homogenous sand composed of rounded to subangular particles measuring ~0.06–0.7 mm in diameter, with a standardized depth of 44 mm (Figure 1). Two different water contents were chosen for each trackway: a low-water content (6–8%) and a high-water content (10–12%), following (Raichlen et al., 2010). Similar sand/hydration levels have been used in other studies and are reported to have a similar consistency to the Laetoli, Tanzania substrates (Crompton et al., 2012), and are considered here as a proxy for other environments from which forensic traces may be recovered.

Participants were instructed to walk across each of the substrates five times at a steady speed. This process

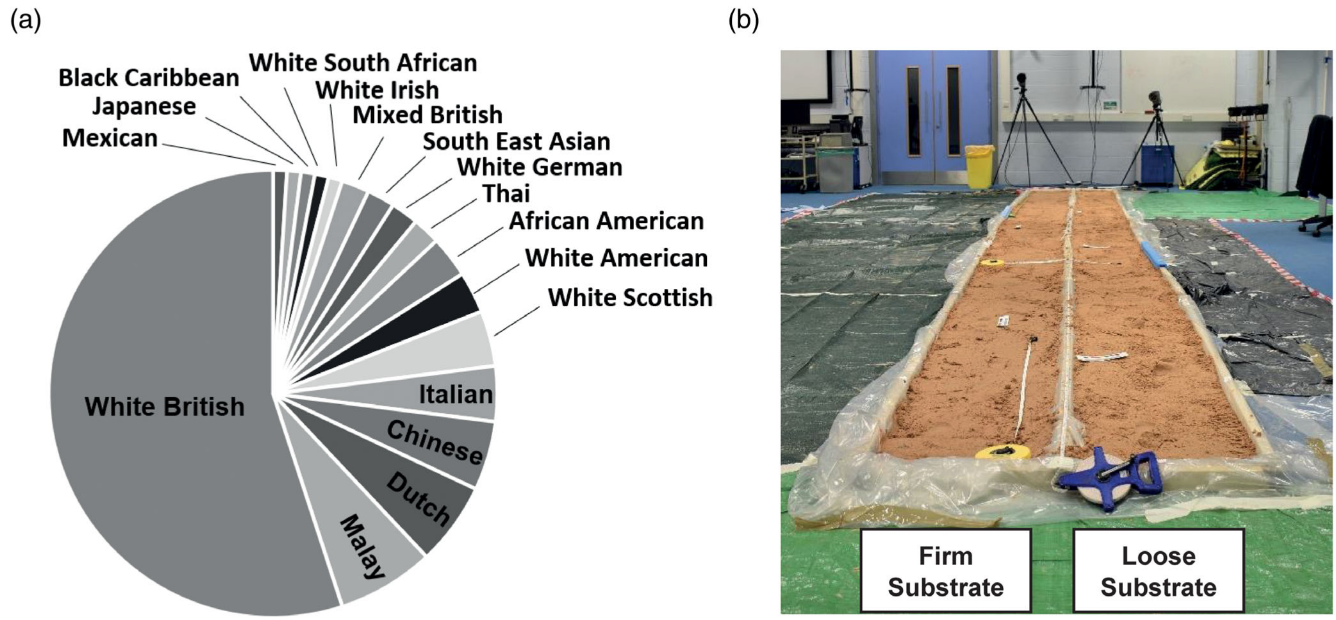

FIGURE 1 (a) Breakdown of the self-identified ethnicities of the participants involved in this study. (b) Photograph of the laboratory set-up

was repeated twice more, but at faster speeds. Between each individual trial, the experimental trackways were flattened and leveled using a screed to ensure that all steps were conducted on a flat, even surface. Speed was controlled for each repeated movement via the use of timing gaits (Browser TCi Timing System). If speed differed by >1 m/s, then the trial was discarded and recaptured.

The trackways were photographed after the final motion from each set of repeated trials. This resulted in six trackways being recorded per participant in total ($n = 100$ participants). All trackways were recorded using a handheld Black Nikon DSLR 5500, with a zoom length of 24 mm. An ISO of 200 was selected, with an aperture of f4 and an exposure of 1/40. Photogrammetry was used to create 3D models of the tracks in Pix4Dmapper (v.4.327 Pix4D, Lausanne, Switzerland) from which measurements of the footprints were extracted (described in detail below).

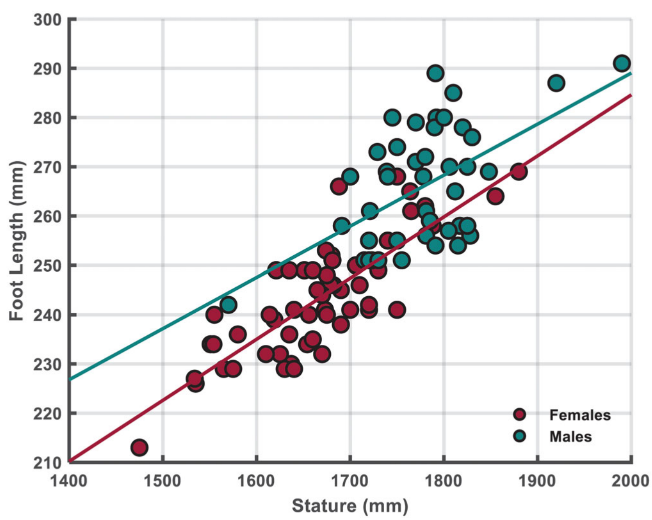

FIGURE 2 Regression of stature to total foot length as measured using an osteometric foot board in males (green) and females (red)

2.2 | Stature predictions

Stature was regressed against true foot length as measured during the experiments using a foot/osteometric board. True foot length was regressed against stature to confirm that length is positively associated with stature for the current population. A strong positive correlation was established in females ($R^2 = .806$; $t = 12.765$; $p \leq .001$) and a moderate correlation in males ($R^2 = 0.550$; $t = 5.627$; $p \leq .001$) (Figure 2), signifying that stature can be reliably predicted from track length in the tested population (Kanchan et al., 2012; Krishan, 2007), permitting the following assessments. Previous studies have also found similar correlations between foot length and stature in which the relationship is not perfect, but weakly correlated.

Footprint length was measured on all 3D models of the tracks in CloudCompare (v.2.10 OpenGL 2018). Footprint length was defined as the distance from the tip of the hallux to the most distal point of the heel (Figure 3). Stature was predicted from footprint length for all

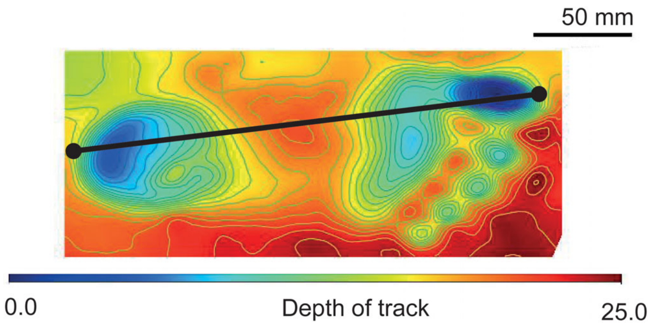

FIGURE 3 Example of a 3D model of a footprint. Footprint length (black line) as measured in this study

participants using Robbin's ratio (1985) and Martin's ratio (1914).

Before determining the variability of footprint dimensions, sources of error needed to be identified. Error may be introduced in two ways: observer error and via intratrack variability. Therefore, replicability tests were computed to test observer error via assessing the reliability of measuring linear measurements from tracks. A two-tailed Student's *t* test for unequal variances was computed to (1) quantify observer error using repeated measurements of the same tracks on randomly selected individuals ($n = 5$ participants; $n = 40$ tracks); and (2) assess the *SE* of step-to-step variance to define intratrack variance ($n = 100$ participants).

As intratrack variance was identified to exceed that of observer error (Tables S1 and S2), then all measurements pertaining to a single individual were averaged. A two-tailed paired Student's *t test* for sampled means was computed to test for disparity between measurements belonging to the same individual but produced on different substrates at various speeds to determine if track dimensions remain consistent when created in substrates of varying compliancy at several speeds. Using true stature as measured during the experiments, a ratio of footprint length per condition to that of stature was calculated and compared using a paired Student's *t test*. Finally, to determine if track measurements change linearly between individuals, the percentage change and *SE* in measurements between the two substrates were calculated. All statistics were computed in R (R Core Team 2017). The percentage change and *SE* in measurements between different speeds across the two substrates were also calculated.

3 | RESULTS

Measuring footprint length from footprints made in different substrates can be reliably accomplished due to low observed measurement error (Table 1). Error may be introduced in two ways when taking measurements of tracks: observer error and via intratrack variability. Replicability tests were computed to test observer error via assessing the reliability of measuring linear measurements from tracks. The *MSE* of all measurements was determined to be <1.07% (Table 1). The threshold for observer error was thus established to be within 0–1.07%.

Step-to-step variance likely exists in a single trackway (Bennett & Morse, 2014). To examine intraprint variability, the *SE* of all measurements taken from an individual trackway was calculated (Table 1). As demonstrated by the M*SE* of each measurement, intratrack variability exceeds that of the observer error, ranging from 2.90% to 4.06%. To circumvent the issue of intratrack variability in linear measurements introducing noise error to between-group assessments, all subsequent analyses used averaged linear measurements (≥9 prints per individual).

Next, we determined the variability from an individual's track dimensions when traversing at the same speed across different substrates. No differences were established in footprint length between the firm and the loose substrate when walking, as shown by a paired Student's *t* test (firm substrate mean, henceforth $M_F = 257.807$ mm; Loose substrate mean, henceforth $M_L = 258.662$ mm; $SD = 13.454$) ($t[97] = -1.330$, $p > .05$) (Table 2). Similarly, no significant difference was found between footprint lengths made on the different substrates when fast walking ($M_F = 263.182$; $M_L = 262.962$; $SD = 16.904$) ($t[97] = -1.700$, $p \leq .001$). However, footprint lengths between different substrates differed once a participant was jogging. In this case, foot length was found to be significantly shorter in the loose substrate compared to the firm substrate, as shown by a paired Student's *t* test ($M_F = 252.478$; $M_L = 259.150$; $SD = 10.473$) ($t[97] = -3.875$, $p \leq .001$).

We also sought to determine the affinity or disparity in footprint lengths created when traversing at different speeds across the same substrate (e.g., is a footprint longer if walking vs. jogging?). If comparing tracks created from a fast walk with those created from a jogging pace, significant differences in footprint length were present in which footprint lengths were determined to be longer if created on the firmer substrate rather than the softer substrate ($M_F = 263.182$; $M_L = 252.478$; $SD = 18.978$) ($t[97] = 3.582$, $p = .001$), as shown by a paired Student's *t* test (Table 2).

Intratrack length was, on average, greater by only $0.39 \pm 6.57\%$ for tracks created on the less compliant substrate. However, if speed is considered as a covariate then track length was always identified to be longer on the firmer substrate (maximum increase: $2.70 \pm 6.14\%$) rather than the looser substrate (maximum increase:

TABLE 1 Observer error for footprint length from tracks ($n = 5$ participants)

	Observer error		Intratrackway variability	
	***MSE* (%)**	**Variance (%)**	***MSE* (%)**	**Variance (%)**
Walk_loose	0.68	0.454 ± 1.050	4.06	5.513 ± 4.294
Walk_firm	1.11	0.069 ± 1.715	4.03	4.467 ± 3.585
Fast Walk_loose	0.44	−0.416 ± 1.051	4.05	5.707 ± 4.430
Fast Walk_firm	0.80	−0.045 ± 1.242	3.96	4.954 ± 3.720
Jog_loose	0.29	−0.116 ± 0.446	3.30	7.766 ± 5.211
Jog_firm	0.86	−0.798 ± 1.355	2.90	4.603 ± 3.514

Note: Dimensions were consistently measured. Intratrackway variability of each participant's movement across the loose and firm substrates ($n = 100$ participants). Intratrackway dimensions exceeded that of observer-error but were still established to be consistently measured. *MSE* values sorted from minimum (dark green) to maximum (yellow).

TABLE 2 Results of the two-tailed paired Student's *t* test for sampled means of the five linear measurements of each track for grouped motions across the two substrates within this study: loose and firm

	Mean (firm)	Mean (loose)	Mean difference	*SD*	*MSE*	95% confidence interval of the difference		t	R^2	df	*p*
						Lower	Upper				
Walk_loose ~ Walk_firm	257.807	258.662	−1.807	13.454	1.359	−4.504	0.890	−1.330	0.849	97	0.187
Fast Walk_loose ~ Fast Walk_firm	263.182	262.962	−3.063	16.904	1.802	−6.645	0.519	−1.700	0.898	87	0.093
Jog_loose ~ Jog_firm	252.478	259.150	−5.284	10.473	1.363	−8.013	−2.555	−3.875	0.842	58	**<0.001***
Walk_loose ~ Fast Walk_loose	258.662	263.182	−0.623	19.378	2.300	−5.210	3.964	−0.271	0.693	70	0.787
Walk_firm ~ Fast Walk_firm	257.807	262.962	−2.125	16.720	1.957	−6.026	1.776	−1.086	0.744	72	0.281
Fast Walk_loose ~ Jog_loose	263.182	252.478	9.084	18.978	2.536	4.001	14.166	3.582	0.489	55	**0.001***
Fast Walk_firm ~ Jog_firm	262.962	259.15	4.106	18.907	2.729	−1.384	9.596	1.505	0.672	47	0.139

Note: Measurements in mm.

TABLE 3 The reported percentage change in footprint length ($n = 100$ participants)

	Mean change (%)	*SD* (%)	*MSE* (%)	Variance (%)
Walk_loose ~ Walk_firm	0.102	3.571	0.10	0.102 ± 3.571
Fast Walk_loose~ Fast Walk_firm	0.385	2.977	0.39	0.385 ± 2.977
Jog_loose ~ Jog_firm	−2.671	3.092	2.67	−2.671 ± 3.092
Walk_loose ~ Fast Walk_loose	−2.144	4.442	2.14	−2.144 ± 4.442
Walk_firm ~ Fast Walk_firm	−0.436	4.921	0.44	−0.436 ± 4.492
Fast Walk_loose ~ Jog_loose	−0.679	5.819	0.68	−0.679 ± 5.819
Fast Walk_firm ~ Jog_firm	2.695	6.136	2.70	2.695 ± 6.136

Note: Positive value indicates that the linear measurement generally increased between each variable (e.g., the footprint became longer). Negative value indicates that the measurement generally decreased. Percentage difference values are sorted from the minimum (dark green) to maximum (yellow) diverged values to reflect the differences in intratrackway dimensions (color-sorted values do not reflect negative/positive length changes, but rather absolute changes).

0.68 ± 5.82%). A longer track produced in the firmer substrate is most likely a response to the boundaries of the track collapsing after track creation when the material is looser. Strong positive correlations were established for foot length discrepancies between all substrate and speed variables (Table 2).

To determine if track measurements change linearly between individuals, the percentage change and *SE* in measurements between different motions across the two substrates were calculated (Table 3). Footprint length was found to be comparably greater on the loose substrate.

Track lengths did not differ significantly between substrates when walking at the participants' preferred speed. Variations in track dimensions only occur once speed is increased to a fast walk. Once a participant is jogging then measurements produced during different trackway conditions are different. Overall, it was established that track lengths were more consistent on the firmer substrate when speed is increased, than on the loose substrate when traversing at different speeds (e.g., from a walk to a jog).

Our next question was to determine if Robbin's (14%) or Martin's (15%) ratio was more suitable for predicting stature when footprints were made in different substrates at different speeds. The *SE* (a measure of accuracy between the predicted stature value and true stature) for Martin's ratio was lower than that of Robbin's ratio across all comparisons (substrates and speeds). This suggest that Martin's ratio is a more accurate method of predicting stature than Robbin's ratio, indicating that a 14% ratio is too low to predict stature from footprints in all scenarios included in this study (Table 4). A paired Student's t test for equal samples further established that using Robbin's ratio to predict stature ($M_{[\text{Robbins}]} = 1{,}718.951$; $SD = 109.821$) from actual footprint length ($M_{[\text{actual}]} = 1{,}606.670$; $SD = 109.821$) ($t[198] = 2.071$, $p \leq .01$) produces stature values which are significantly shorter than using Martin's ratio ($M_{[\text{Martin}]} = 1{,}809.863$; $SD = 117.672$) ($t[198] = -6.071$; $p \leq .001$).

Our final question was: How do we select the best prediction method for estimating stature from footprints which are made in different substrates and different speeds? We generated seven different ratios of footprint length to total body stature as informed by data from 100 people moving across different experimental substrates. We established that in our tested population which consisted of individuals from various ethnicities, ages, sexes, body weights, and body dimensions, the average ratio of foot length to stature was 14.8%. This ratio changes when walking on firm substrates at walking and fast-walking speeds (15%) to that of walking across the substrate at a jog (15.2%). Three different ratios were established when footprints were created on the softer substrate (Table 5).

TABLE 5 The average ratios for our tested population moving across different substrates at different speeds

	Ratio	% of foot length to stature
Actual foot length	0.148	14.8
Footprint on firm substrate: walk	0.150	15.0
Footprint on firm substrate: fast walk	0.150	15.0
Footprint on firm substrate: jog	0.152	15.2
Footprint on loose substrate: walk	0.151	15.1
Footprint on loose substrate: fast walk	0.147	14.7
Footprint on loose substrate: jog	0.150	15.0

TABLE 4 Percentage errors of the predicted stature from footprints (mean, range, and *SD*) using both Robbin's and Martin's ratios

		Loose substrate				Firm substrate			
		Mean% error	Min. (%)	Max. (%)	*SD*	Mean% error	Min. (%)	Max. (%)	*SD*
Walk	Robbin's ratio	7.440	−4.38	18.56	±5.339	7.460	−7.70	20.32	±5.467
	Martin's ratio	0.278	−13.85	12.30	±5.102	0.296	−10.75	10.66	±4.983
Fast walk	Robbin's ratio	7.312	−3.67	17.15	±5.913	7.652	−8.72	17.78	±6.325
	Martin's ratio	0.158	−10.11	9.34	±5.519	0.450	−14.81	9.93	±5.903
Jog	Robbin's ratio	7.130	−1.08	19.06	±5.098	4.893	−2.07	13.18	±4.084
	Martin's ratio	−2.010	−8.59	5.63	±3.812	−0.012	−7.67	11.13	±4.758
Stature	*Robbin's ratio*	*6.110*	*0.422*	*14.461*	*±3.454*				
	Martin's ratio	*−0.964*	*−6.703*	*6.830*	*±3.223*				

Note: Percentage errors of the stature values predicted from foot length measured during the trials is reported in italics. Mean errors range from small (dark green) to large (red).

4 | DISCUSSION: THE WAY FORWARD

Paleoanthropological applications: Field scientists commonly estimate stature from footprints by using a ratio of footprint-to-stature (Ashton et al., 2014; Bennett et al., 2020; Dingwall et al., 2013; Wiseman et al., 2020) and we sought to determine just how accurate these "one-size-fits-all" approaches are when the conditions which lead to footprint creation are changed (Morse et al., 2013). In the previous section we have illustrated how footprints which are made on different substrates at various speeds produce footprint lengths which are not consistently impressed, that is—the footprint lengths are significantly different when made under differing conditions. It is recommended that these footprint-to-stature ratios are applied to estimate stature of the track-maker rather than a "one-size-fits-all" approach that has been commonly applied in the past. We have provided a table of ratios (Table 5) which can be easily referred to by field scientists and easily adopted by measuring footprint length and applying the provided ratio with respect to the substrate and estimated speed of the track-maker. Speed can be easily estimated by measuring the stride/step length of the trackway, although the authors refer to (Bennett & Morse, 2014) for an overview of other methods which can be applied to predict speed from footprints. The field scientist can also refer to Tables 3 and 4 here to identify the accuracy in which they will be able to estimate stature respective to the conditions under which the footprint was created.

The key here is to use the ratios provided in Table 5 as a simple method to estimate stature from footprints in a variety of settings. Although some of our conditions had a somewhat high *SE*, we do not see this as a cause for concern because previously published footprint datasets have had outliers present (Agnihotri et al., 2007; Dhaneria et al., 2016; Ibeabuchi et al., 2018; Kanchan et al., 2008; Kim et al., 2018). Rather, we recommend that sources of error are clearly identified when estimating stature from footprints, and that the field scientists/practitioners are upfront about the associated potential error margin.

Forensic applications: We recommend that further research is required to refine stature estimation precision for forensic cases from which an individual may be prosecuted due to the likelihood of footprint outline significantly being altered dependent on condition of speed and substrate (Krishan et al., 2015). There are clear recommendations and rigorous protocols which must be followed with respect to the application of forensic methods, including inferences made from footprints recovered from crime scenes (Larsen et al., 2021; Tuttle, 1986). First and foremost, the methodology must be well established, the sources of error must be identified with a clear and concise error margin proclaimed, and finally, the method must be rigorously tested, retested and retestable by all in the future. Therefore, we encourage researchers to add to the ratios provided in Table 5 in the future by testing other substrates with a consideration for speed and how speed affects footprint length. We encourage further research using more rigorous prediction methods to be peer-reviewed and published with consideration of how speed and substrate can affect trace dimensions. Further consideration should be given to possible differences that exist between dynamic traces, such as those reported here, and static traces (Mukhra et al., 2020, 2021; Nirenberg et al., 2019a, 2019b), and with a greater range of substrates assessed. We also stress that this study only assessed barefoot individuals and tests must be performed on footprints of footwear, such as socks (i.e., see Nirenberg et al., 2019a, for a description on sock-clad footprint traces and how footprint dimensions are further changed by the wearing of materials on the foot) and shoes, and how each of these respectively change between static and dynamic traces (Mukhra et al., 2020, 2021). Ultimately, we stress that a "one-size-fits-all" approach (Robbins, 1985) is not suitable for forensic applications.

5 | CONCLUSION

We suggest the use of our ratios provided here for predicting stature from footprint lengths in the recovery/discovery of fossil footprint traces. We actively encourage practitioners/field scientists to continue this research by testing more substrates with a consideration of speed. Naturally, this is particularly pertinent for accurately estimating stature in criminal cases for which this evidence must be rigorously and accurately estimated to be upheld in court, but we cannot ignore the scientific importance of this research for the study of fossil footprints.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Ashleigh Wiseman: Data curation (lead); formal analysis (lead); investigation (lead); methodology (equal); project administration (equal); validation (equal). **Isabelle**

De Groote: Conceptualization (equal); formal analysis (supporting); funding acquisition (lead); investigation (supporting); methodology (supporting); supervision (lead); validation (equal).

DATA AVAILABILITY STATEMENT

All metadata are freely available upon request to the authors.

ETHICS STATEMENT

Ethical approval was granted by the Liverpool John Moores University Research Ethics Committee (REC: 16/NSP/041).

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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