Volume XII ● Issue 2/2021 ● Pages 143–154

INTERDISCIPLINARIA ARCHAEOLOGICA
NATURAL SCIENCES IN ARCHAEOLOGY

homepage: http://www.iansa.eu

Orientation Patterns Characteristic for the Structure of the Ceramic Body of Wheel-thrown Pottery

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A R T I C L E I N F O

Article history:
Received: 19th February 2021
Accepted: 6th October 2021

DOI: http://dx.doi.org/10.24916/iansa.2021.2.3

Key words:
orientation analysis
wheel throwing
pottery forming
image analysis
thin section petrography

A B S T R A C T

The described analysis follows recent findings related to the orientation of particles and voids in a ceramic body that is characteristic for wheel-made pottery. The analysis is focused on the potential variability within wheel-throwing method and is based on an experimental collection that combines the factors of the experience and motor habits of individual potters and the vessel shape. The orientation of the components of a ceramic body is calculated for two sections: radial and tangential. The sections are analysed using optical microscopy. The calculated orientation and alignment reflect the throwing style of potters using the same forming method.

1. Introduction

During the past decade, we have been developing a methodology based on quantification of the orientation and alignment of the components of a ceramic body as one of the principal features reflecting pottery-forming techniques that are theoretically observable on every sherd (Thér, 2016; Thér *et al.*, 2019; Thér and Toms, 2016). Many of the phenomena that occur on the surface of pottery fragments and can be related to pottery-forming practices are randomly preserved, and their interpretation is further complicated by the common practice of combining several techniques during the forming and finishing of vessels. One diagnostic attribute can, at least theoretically, be observed on every ceramic sherd – the orientation of the structure of the ceramic body. The relationship between forming techniques and the orientation of the components of the ceramic material has long been recognised (Balfet, 1953; Bordet and Courtois, 1967; Felts, 1942; Gifford, 1928; Linné, 1925, p.33; Shepard, 1956, pp.183–184). The application of physical force to the plastic clay during forming is the main factor affecting the alignment of the components. The resulting orientation and alignment are characteristic of each forming method, although some orientation patterns might result from more than one fabrication process (for an overview of the assumptions for particular techniques see Berg, 2008, Figure 1; Carr, 1990; Courty and Roux, 1995, Table 1; Livingstone Smith, 2007, pp.88–146; Middleton, 2005, Figure 4.8; Pierret, 1995, pp.46–50; Roux, 2019, Figure 3.20; Rye, 1981, pp.58–89; Thér, 2020, Figure 9; Whitbread, 1996).

Measurement of the orientation refines the analysis of preferred orientation by defining the exact intervals of orientation variability for the individual forming techniques and their combinations. For the measurements, we selected two basic sections: sections perpendicular to the wall surface in the plane parallel to the vessel height (hereinafter referred to as a *radial section*) and sections tangential to the vessel wall cut through a core zone of the wall (hereinafter referred to as a *tangential section*). Originally, we captured three transects approx. 6 mm wide in each thin section at a magnification of 40 times in plane-polarised light using a standard petrographic microscope. The resultant images have a resolution of 1.09 µm. Then inclusions and voids were extracted using object extraction and separation methods in

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Table 1. Orientation analysis results for experimental samples taken in tangential and radial sections. MD – Mean direction, CSD – Circular standard deviation.

Sample	Min. thickness	Max. thickness	Diff. in thickness	Shape	Author	Wheel	Radial sections		Tangential sections	
							MD	CSD	MD	CSD
1	3797	4910	1113	Bowl	Henry	Motorised	7	35	28	36
2	4048	5001	953	Bowl	Henry	Motorised	5	33	19	30
3	3945	5125	1180	Bowl	Henry	Motorised	3	36	27	38
4	4806	5807	1001	Bowl	Henry	Motorised	3	35	27	31
5	4833	5617	784	Bowl	Henry	Motorised	3	39	41	23
6	5022	5587	565	Bowl	Henry	Motorised	4	35	34	37
7	3809	4265	456	Bowl	Henry	Motorised	4	39	22	31
8	3492	4377	885	Bowl	Henry	Motorised	1	36	38	37
9	3672	4415	743	Bowl	Henry	Motorised	4	33	25	34
10	4080	4550	470	Bowl	Henry	Motorised	5	33	51	31
11	4026	4318	292	Bowl	Henry	Motorised	7	33	38	35
12	4043	4393	350	Bowl	Henry	Motorised	1	35	42	31
13	3830	4021	191	Bowl	Henry	Motorised	1	32	39	38
14	3672	3979	307	Bowl	Henry	Motorised	6	31	42	35
15	3784	4373	589	Bowl	Henry	Motorised	7	30	23	30
16	3616	4229	613	Conical v.	Henry	Motorised	15	28	21	33
17	3311	3742	431	Conical v.	Henry	Motorised	19	26	37	34
18	3510	4471	961	Conical v.	Henry	Motorised	14	27	31	35
19	4372	5651	1279	Conical v.	Henry	Motorised	14	34	39	38
20	3956	5156	1200	Conical v.	Henry	Motorised	9	33	45	33
21	4040	5329	1289	Conical v.	Henry	Motorised	13	32	35	35
22	4395	4700	305	Conical v.	Henry	Motorised	30	42	18	17
23	3934	4593	659	Conical v.	Henry	Motorised	24	39	19	21
24	4197	4538	341	Conical v.	Henry	Motorised	25	40	19	20
25	4446	4970	524	Conical v.	Henry	Motorised	13	29	32	31
26	4549	5163	614	Conical v.	Henry	Motorised	15	28	43	41
27	4476	5379	903	Conical v.	Henry	Motorised	14	31	43	38
28	3213	5175	1962	Conical v.	Henry	Motorised	17	35	23	24
29	4554	5529	975	Conical v.	Henry	Motorised	22	32	26	22
30	4617	5977	1360	Conical v.	Henry	Motorised	16	33	26	29
31	2680	3270	590	Bowl	Peter	Motorised	5	29	29	33
32	3150	3177	27	Bowl	Peter	Motorised	5	32	16	38
33	3151	3617	466	Bowl	Peter	Motorised	8	32	19	34
34	3971	4362	391	Bowl	Peter	Motorised	9	29	37	36
35	3294	4134	840	Bowl	Peter	Motorised	8	32	45	40
36	3417	3859	442	Bowl	Peter	Motorised	10	30	47	40
37	3743	4146	403	Bowl	Peter	Motorised	0	38	24	28
38	3658	4372	714	Bowl	Peter	Motorised	2	32	38	43
39	3666	4086	420	Bowl	Peter	Motorised	8	35	28	30
40	3738	4265	527	Bowl	Peter	Motorised	8	33	18	29
41	3598	4154	556	Bowl	Peter	Motorised	11	34	24	33
42	3871	4282	411	Bowl	Peter	Motorised	12	31	24	32
43	3087	4234	1147	Bowl	Peter	Motorised	7	38	20	32
44	3691	4187	496	Bowl	Peter	Motorised	9	38	32	25
45	3727	4185	458	Bowl	Peter	Motorised	11	34	27	26
46	4849	5931	1082	Conical v.	Peter	Motorised	13	37	21	20
47	4885	5,10E+03	215	Conical v.	Peter	Motorised	12	28	26	24
48	4227	5013	786	Conical v.	Peter	Motorised	6	30	35	23
49	4094	5015	921	Conical v.	Peter	Motorised	12	30	21	30
50	4550	5016	466	Conical v.	Peter	Motorised	36	45	21	30
51	4643	5404	761	Conical v.	Peter	Motorised	8	34	32	27

Table 1. Orientation analysis results for experimental samples taken in tangential and radial sections. MD – Mean direction, CSD – Circular standard deviation. (*Continuation*)

Sample	Min. thickness	Max. thickness	Diff. in thickness	Shape	Author	Wheel	Radial sections		Tangential sections	
							MD	CSD	MD	CSD
52	4620	5395	775	Conical v.	Peter	Motorised	26	34	20	21
53	4038	4897	859	Conical v.	Peter	Motorised	22	30	13	18
54	4490	5162	672	Conical v.	Peter	Motorised	18	44	13	26
55	5061	6,15E+03	1091	Conical v.	Peter	Motorised	13	38	22	29
56	4619	5163	544	Conical v.	Peter	Motorised	5	27	21	21
57	4601	5274	673	Conical v.	Peter	Motorised	11	25	21	24
58	3890	4120	230	Conical v.	Peter	Motorised	18	40	26	27
59	4716	5365	649	Conical v.	Peter	Motorised	27	51	27	22
60	4783	5099	316	Conical v.	Peter	Motorised	7	31	31	20
61	8824	9686	862	Conical v.	Peter	Flywheel	21	34	17	35
62	8832	9545	713	Conical v.	Peter	Flywheel	19	36	15	28
63	8981	9604	623	Conical v.	Peter	Flywheel	22	40	18	28
64	8493	10159	1666	Conical v.	Peter	Flywheel	13	36	4	27
65	7870	8400	530	Conical v.	Peter	Flywheel	16	35	12	31
66	8607	11098	2491	Conical v.	Peter	Flywheel	17	33	17	31
67	3965	6019	2054	Bowl	Thomas	Motorised	10	30	6	41
68	3916	5497	1581	Bowl	Thomas	Motorised	12	34	16	39
69	3554	5511	1957	Bowl	Thomas	Motorised	3	34	5	32
70	4216	6451	2235	Bowl	Thomas	Motorised	9	35	17	34
71	4349	6475	2126	Bowl	Thomas	Motorised	18	33	11	32
72	3926	5816	1890	Bowl	Thomas	Motorised	16	35	17	28
73	3702	7127	3425	Bowl	Thomas	Motorised	14	40	13	28
74	3947	6606	2659	Bowl	Thomas	Motorised	15	37	11	32
75	3771	6335	2564	Bowl	Thomas	Motorised	23	36	11	32
76	4282	5291	1009	Bowl	Thomas	Motorised	9	40	19	33
77	4256	5658	1402	Bowl	Thomas	Motorised	13	44	13	31
78	4364	6078	1714	Bowl	Thomas	Motorised	11	41	20	29
79	3273	5742	2469	Bowl	Thomas	Motorised	8	32	7	36
80	2954	5773	2819	Bowl	Thomas	Motorised	8	35	11	35
81	3542	6477	2935	Bowl	Thomas	Motorised	11	39	9	35
82	6513	8194	1681	Conical v.	Thomas	Motorised	13	40	35	39
83	6219	7205	986	Conical v.	Thomas	Motorised	22	41	18	36
84	6471	8063	1592	Conical v.	Thomas	Motorised	11	36	10	29
85	6773	7352	579	Conical v.	Thomas	Motorised	15	40	17	37
86	6715	7233	518	Conical v.	Thomas	Motorised	20	37	24	36
87	7120	7343	223	Conical v.	Thomas	Motorised	20	37	16	38
88	7179	8131	952	Conical v.	Thomas	Motorised	19	40	11	30
89	7535	8166	631	Conical v.	Thomas	Motorised	16	41	29	37
90	7305	8214	909	Conical v.	Thomas	Motorised	19	42	25	37
91	6786	7729	943	Conical v.	Thomas	Motorised	11	39	8	39
92	6775	7370	595	Conical v.	Thomas	Motorised	8	36	16	40
93	6969	7340	371	Conical v.	Thomas	Motorised	8	36	18	34
94	7923	9060	1137	Conical v.	Thomas	Motorised	8	35	14	28
95	7477	9114	1637	Conical v.	Thomas	Motorised	21	33	22	30
96	8476	8922	446	Conical v.	Thomas	Motorised	19	33	17	39

JMicroVision software (Roduit, 2014). Two basic measures were chosen to express the object orientation: (a) mean direction (MD) – average orientation of objects, and (b) circular standard deviation (CSD) – the dispersion of the values from the average (Fisher, 1993, pp.75–78; Mardia and Jupp, 2000, pp.15–19).

In the first experimental collection, we found several significant markers distinguishing wheel finishing,

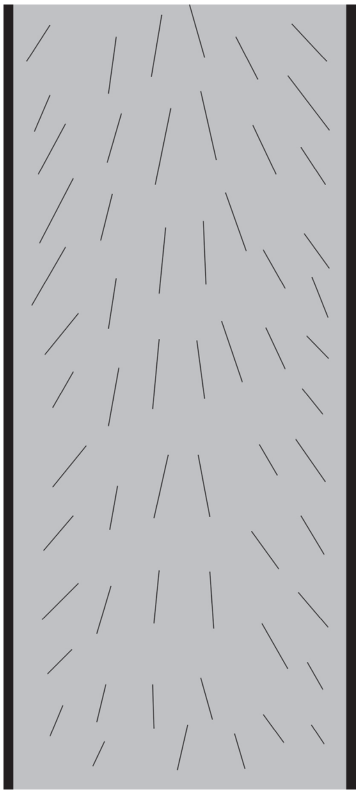

Figure 1. Imbricate pattern – orientation pattern typical for wheel throwing observed in radial sections. The upper ends of the objects in the marginal zones of wheel-thrown pottery incline inwards towards the core of the wall.

wheel shaping, and wheel throwing as basic levels of the contribution of rotational movement in pottery forming[1], especially in the mean directions in core areas of radial sections, in CSD in core areas of radial sections or the mean direction in tangential sections (Thér, 2016).

In the second experimental dataset, we focused directly on the distinctions among different uses of the potter's wheel. In this dataset, we evaluated the effect of the degree of transformation of the clay mass, the shape of the vessel, the velocity of rotation or the individual experience and skills of the potter. The principal finding of the analysis of the second experimental collection was that the specific characteristics of the orientation of wheel-thrown samples are developed especially in the lower parts of the vessels. The significant difference between the results obtained from lower and upper parts of the experimental vessels can be seen especially in the tangential sections. The difference is due to the fact that the lower part of the vessel undergoes a strong transformation when the potter creates a basic form prepared for lifting. While she/he lifts the clay mass upward, the rest of the clay is lifted above the fingers but is not affected by their movement (Thér and Toms, 2016, pp.38–39).

The analysis of the second experimental series also confirmed the observation made in the first experimental series, namely that the upper ends of the objects in the marginal zones of wheel-thrown pottery incline inwards towards the core of the wall (Figure 1). We called this phenomenon "imbricate pattern" and suggested that this pattern is caused by shear stress induced by upward movements of the fingers during wheel throwing. The clay mass in the margins moves more quickly during lifting than the mass in the core of the wall. Therefore, marginal zones can be seen as shear zones with a predominance of shear stress. The comparison of internal and external areas shows that the inclination of the inclusions and voids inwards is more strongly developed in the external area. We explained this phenomenon by the disproportion of the forces required on the interior and exterior of the vessel, which causes larger shear deformation on the exterior area of the vessel wall and subsequently a more pronounced imbricate pattern in this area (Thér and Toms, 2016, p.38).

In the third experimental series described in this study, we focused solely on the orientation patterns resulting from wheel throwing and especially on those variables whose significant effect became the subject of hypotheses after evaluating the previous series.

a) Above all, the shape of the vessel is important. The analysis suggested that the shape significantly influences the orientation parameters. Samples taken from the oblate ellipsoid fashioned in the second experimental series showed below-average CSD values in radial sections from the lower parts of the vessels but, more importantly, a significant increase in CSD and lesser deviation from the horizontal axis in tangential sections (Thér and Toms, 2016, Figures 5 and 7). The distortion from typical wheel-throwing values for conical shapes could be hypothetically proportional to the degree of transformation that is required to finish the shape of the vessel extra to the lifting of the clay.

b) The second experimental series also showed that the orientation patterns reflect the equilibrium established between the potter´s actions and tools she/he uses during forming. If the potters use an unfamiliar clay or rotational device or throw an unusual shape, they disturb the equilibrium gained by experience and thus also the alignment typical for the

[1] There are two basic ways to classify variants of the application of rotational movement in the pottery-forming sequence. The first approach classifies individual combinations of the techniques applied at different stages of the forming. The forming methods are then referred to as, for example, wheel coiling or wheel moulding (Berg, 2009; Roux, 2019; 2017; Rückl and Jacobs, 2016; Thér and Toms, 2016). An alternative approach is to separately define the variants of the use of rotational movement and define them independently of the other techniques (Berg, 2008; 2007; Choleva, 2012; Courty and Roux, 1995; Henrickson, 1991; Roux, 2003; Roux and Courty, 1998; Thér, 2016; Thér *et al.*, 2017; Thér and Toms, 2016). The differences in the contribution of rotational movement to the whole forming sequence are the main criterion in this classification:
(a) *Wheel finishing*. The vessel is formed by some hand-building technique and subsequently the rotational movement is used for surface modifications and minor shape corrections, *i.e.* only in the finishing stage.
(b) *Wheel shaping*. A roughout of the vessel is formed by some hand-building technique and subsequently rotational kinetic energy (RKE) is used to shape and thin the vessel walls. This technique can be used in assembling and finishing the vessel.
(c) *Wheel throwing*. The entire forming sequence is performed using RKE. The main interest of the orientation analysis is to define the relation between the contribution of rotational movement in forming and orientation patterns: thus, we use the second approach to classification.

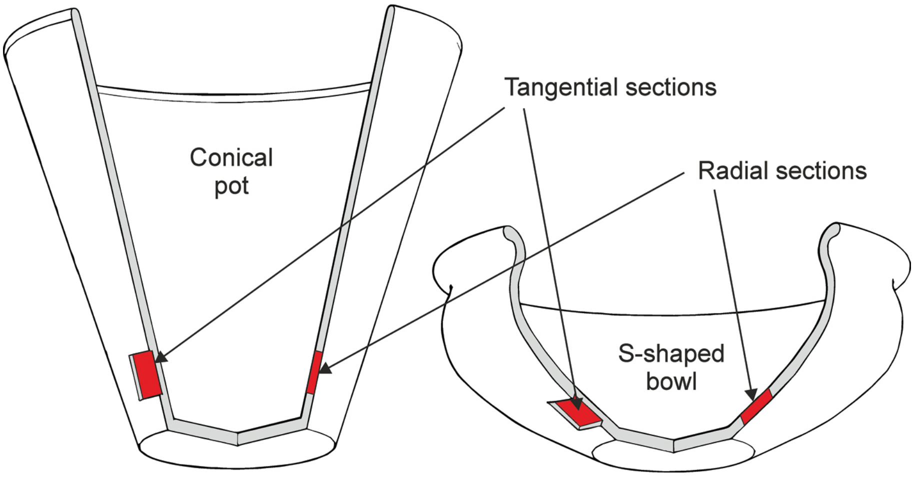

Figure 2. Experimentally-replicated vessels' shapes with the location of tangential and radial sections.

technique. This especially applies to the beginner for whom all the components of the technique are new (Thér and Toms, 2016, Figure 7). In this current, third experimental series we compared three professional potters who routinely produce pottery, to see whether the results are comparable when the potters have (a) a similar, high level of skill, (b) create shapes that do not differ significantly from what they are used to forming on a wheel, and (c) use familiar tools, *i.e.* potters are in equilibrium with their working environment.

2. Materials and method

The third experimental collection is focused on the variability of orientation patterns within the wheel-throwing method. So far, one principal experienced potter with 23 years of experience in wheel throwing, Peter Toms, was employed in our experiments. Along with Petr Toms (hereinafter referred to as Peter) we included two other professional potters: Jiří Lang (hereinafter referred to as Henry) and Tomáš Macek (hereinafter referred to as Thomas).

Two different vessel shapes were replicated: a simple conical vessel 180 mm in height and 200 mm in diameter at the top and an S-shaped bowl 85 mm in height and 200 mm in diameter at the top (depicted in Figure 2). The S-shaped bowl was chosen because, in our application of the methodology, we are dealing mainly with Late Iron Age pottery in Central Europe, and this is the most common shape of wheel-made pottery in this context.

Each potter formed 15 slightly conical pots and 15 S-shaped bowls. The target wall thickness for all the containers was 5 mm. No other parameters of the forming method were specified in order not to force the potters to employ motions that are not "natural" for them. All the potters used their wheels (motor-driven) and the same fine-grained commercial clay – Witgert 10. The experimental collection was created during one session in one pottery workshop after the potters became acquainted with the selected pottery shapes. The speed of the wheels was measured by a laser tachometer.

The dataset was complemented by six conical vessels thrown by Peter on a replica of a flywheel made of a wooden-spoked wheel. The device is located in the Archaeological park of prehistory in Všestary (Czech Republic). Peter does not work on this wheel on a regular basis and there was a minor technical problem related to fitting the wheel socket in the axis which caused vibrations of the wheel when a certain speed was reached.

Two oriented thin sections were cut from the lower body of each experimental vessel: tangential and radial (Figure 2). The entire area of each thin section was recorded at a magnification of 200× using a Keyence VHX6000 digital microscope. The resultant images have a resolution of 1.11 µm. The analysis followed the published methodology (Thér, 2016; Thér and Toms, 2016), except for the software treatment. The components of the ceramic materials were extracted using automatic area measurement tools available in the Keyence VHX6000 measurement software. The range of threshold values chosen to separate inclusion and void representations was based primarily on colour saturation, which shows the best results for the thin sections with uneven thickness (resulting in uneven brightness of the captured image).

The extracted objects in the radial sections were analysed only in the external zones of the section (one-third of the thickness adjacent to the outer edge). The focus on the external area follows the results of the analysis of the

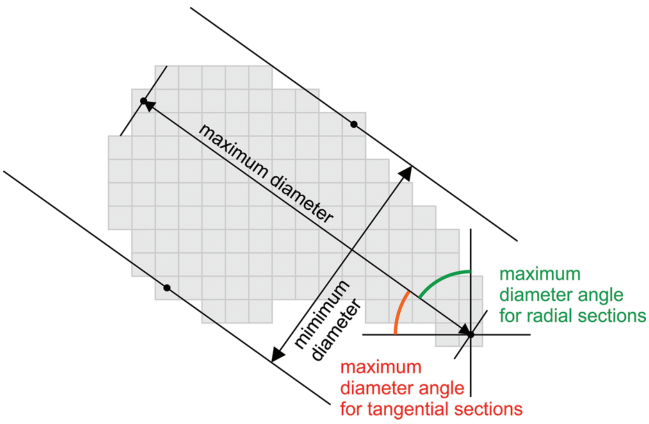

Figure 3. Descriptors of the separate objects relevant to the analysis.

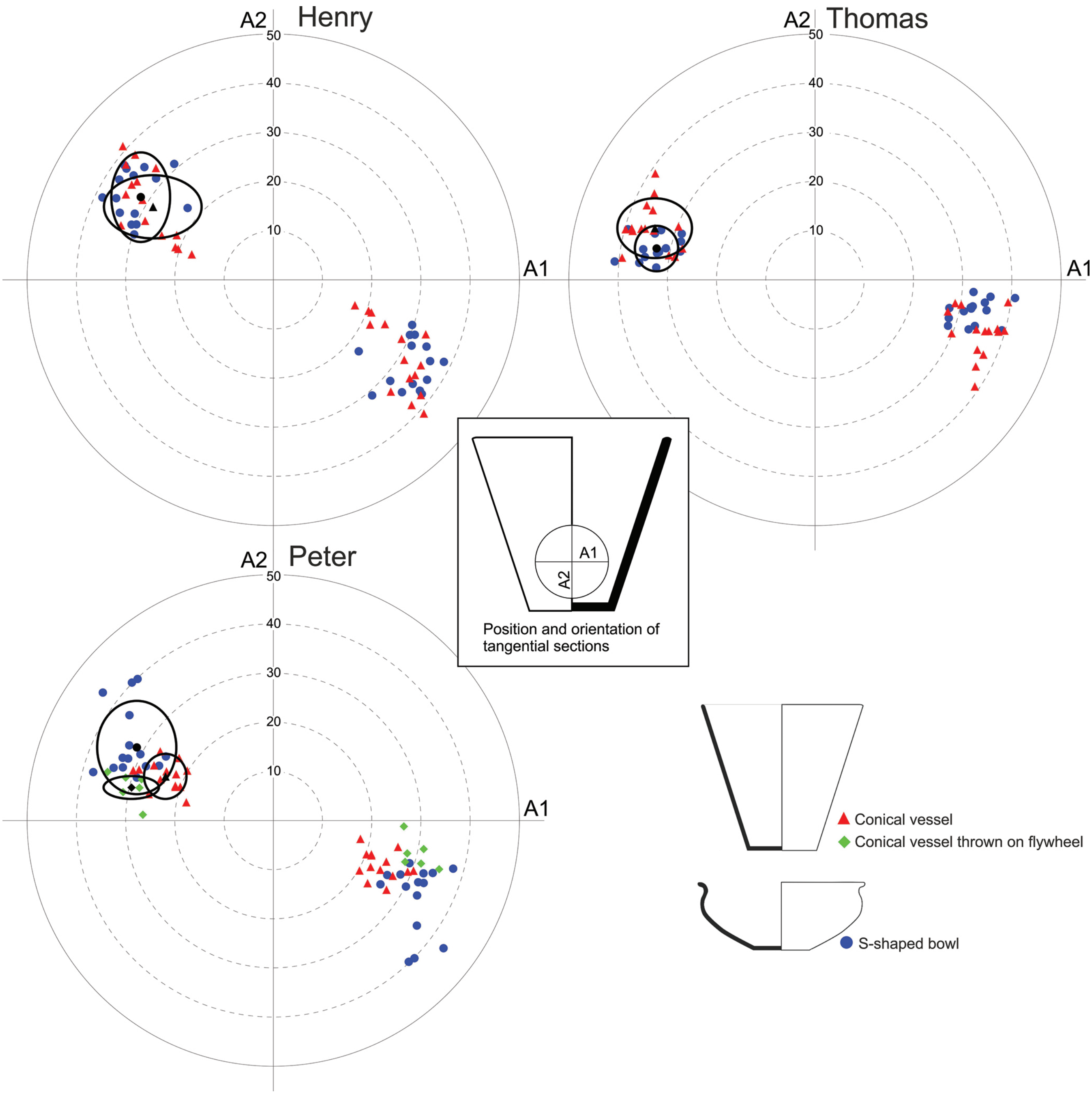

Figure 4. Orientation of inclusions and voids in tangential sections.

second experimental series which showed that the typical imbrication pattern is more strongly developed in the external area (Thér and Toms, 2016, Figure 4). The extracted objects were characterised by a set of descriptors relevant to the analysis (Figure 3): a) maximum diameter – the maximum length between any two points that lie on the inner perimeter of the object; b) minimum diameter – the minimum possible distance between two parallel lines on either side of the object, this is calculated as the distance between the pixels that each of the two lines touches; c) elongation – aspect ratio of the object (maximum diameter/minimum diameter); d) orientation – the angle between the object's maximum diameter axis and the horizontal axis read clockwise for tangential sections and the angle between the object's maximum diameter axis and the vertical axis read counter-clockwise for radial sections.

Two basic measures were chosen to express the object orientation: (a) mean direction, and (b) circular standard deviation (CSD) (Fisher, 1993, pp.75–78; Mardia and Jupp, 2000, pp.15–19). The raw data are plotted in a polar coordinate system. Each point in the diagram is determined by an angle from a reference direction which represents the mean direction of the objects of the given sample and the distance from the centre of the circle which represents the CSD values. The calculated orientations are an axial type of data. Axial data consist of an undirected line – either end of

Table 2. Descriptive statistics of orientation, alignment, and wall thickness of experimental samples according to the observed variables.

		Henry		Peter			Thomas	
	Potter	**Henry**		**Peter**			**Thomas**	
	Shape	**Bowl**	**Conical v.**	**Bowl**	**Conical v.**		**Bowl**	**Conical v.**
	Wheel	**Motorised**	**Motorised**	**Motorised**	**Motorised**	**Flywheel**	**Motorised**	**Motorised**
Number of Observations		15	15	15	15	6	15	15
Av. thickness (mm)		4.4	4.5	3.8	4.9	9.2	5	7.5
Standard deviation of thickness (mm)		0.5	0.5	0.3	0.4	0.5	0.3	0.6
Av. diference in thickness (mm)		0.7	0.9	0.5	0.7	1.1	2.2	0.9
Tangential sectons	Mean Vector (μ)	32.983	30.411	28.446	23.21	13.902	12.405	18.673
	Circular Standard Deviation	8.977	9.185	9.287	6.108	5.109	4.487	7.078
	99% Confidence Interval (–/+) for μ	26.349	23.623	21.583	18.695	6.742	9.087	13.441
		39.617	37.199	35.309	27.726	21.062	15.722	23.905
Radial sections	Mean Vector (μ)	3.988	17.306	7.585	15.473	17.688	11.976	15.419
	Circular Standard Deviation	2.082	5.351	3.143	8.495	3.055	4.637	4.921
	Standard Error of Mean	0.597	1.536	0.902	2.437	1.662	1.331	1.412
	99% Confidence Interval (–/+) for μ	2.449	13.35	5.262	9.194	13.406	8.548	11.781
		5.527	21.262	9.909	21.751	21.97	15.404	19.057

the line could be taken as the direction; therefore, the data are represented by both possible directions, *i.e.*, each sample is plotted by a pair of points.

3. Results

The work of each of the potters can be characterised by a slightly different orientation pattern (all the measurements are summarised in Table 2). Peter's conical vessels show a coherent group corresponding to the previous findings in orientations and alignment in tangential sections (average deviation from horizontal axis 21° and CSD 24°), the bowls exhibit similar orientation (average MD 27°), but a significant increase in CSD (33° on average) with extremes exceeding 40° (Figure 4). A significant difference can also be observed in the radial sections. The conical vessels have significantly more developed inward inclination (15° on average) compared to the bowls (8° on average; Figure 5). While the thickness of the conical vessel walls (measured in the area of the sample) roughly corresponds to the specified thickness (4.8 mm on average, standard deviation of 0.4 mm), the wall thickness of the bowls is significantly lower (3.8 mm on average, standard deviation of 0.3 mm; Figure 6). Throwing of pots on the flywheel results in a decrease in the deviations from the horizontal axis (average MD 16°, average CSD 30°). The thickness of the walls (9.2 mm on average, standard deviation of 0.6 mm; Figure 6) demonstrates the difficulty that the potter encountered when using non-standard and technically-unadjusted equipment.

Conical vessels and bowls cannot be reliably differentiated in the production by Henry. Both show a higher average deviation from the horizontal axis (average MD: conical v. 31°, bowls 34°) than Peter's vessels. The average CSD is similar (conical v. 33°, bowls 34°) and comparable with the bowls produced by Peter. Only a small proportion of the conical vessels exhibit CSD below 30° (Figure 4). In contrast, there is a difference in the inward inclination between conical vessels and bowls in the radial sections. The difference is similar to that of Peter's samples but more pronounced: conical vessels – 17° on average, bowls – 4° on average (Figure 5). The wall thickness of the conical vessels (4.5 mm on average, standard deviation of 0.5 mm) and bowls (4.4 mm on average, standard deviation of 0.5 mm) is similar and corresponds with the assigned thickness (Figure 6).

Both the shapes fashioned by Thomas show lower mean deviation from the horizontal axis than the vessels fashioned by the previous two potters and there is a significant difference between them in this respect. The bowls exhibit lower deviation than the conical vessels (conical v. 17° on average, bowls 11° on average). Thomas' vessels are very similar in alignment (average CSD: conical v. 33°, bowls 34°) to those of Henry (Figure 4). No significant difference can be seen in the radial sections: the average MD of the conical vessels is 15° and bowls 12° (Figure 5). The conical vessels are significantly thicker than required (7.5 mm on average, standard deviation of 0.6 mm). The bowls have an average thickness of 4.9 mm (standard deviation of 0.3 mm; Figure 6). The significantly higher difference in the wall thickness compared to other assemblages reflects the unevenness of the walls in the lower parts of the bowls (the walls taper upwards; Figure 7).

4. Discussion

The results point to interesting differences among the potters. All three potters came from different learning environments. They used motor-driven potter's wheels (except for the manually-driven flywheel). Peter and Henry

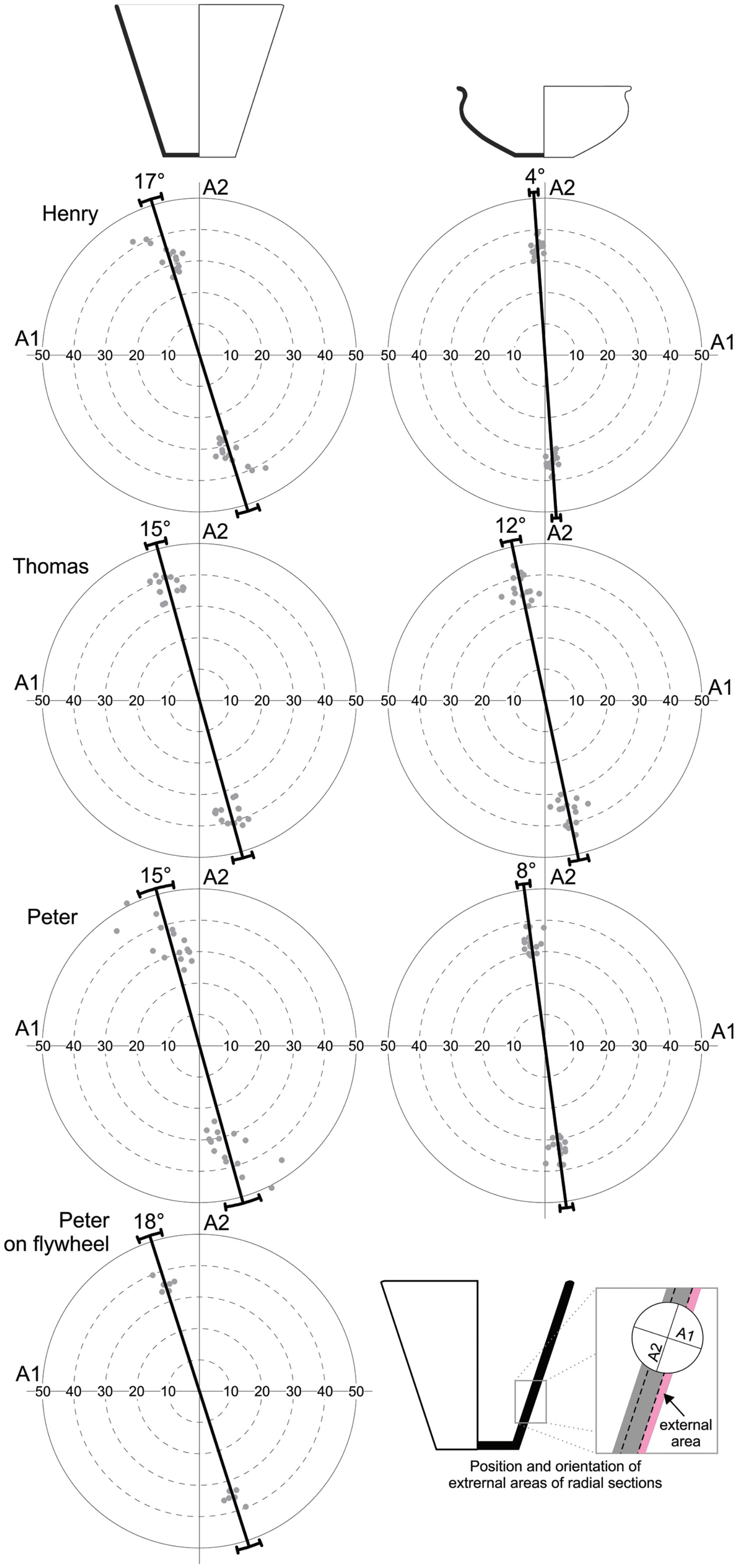

Figure 5. Orientation of inclusions and voids in radial sections.

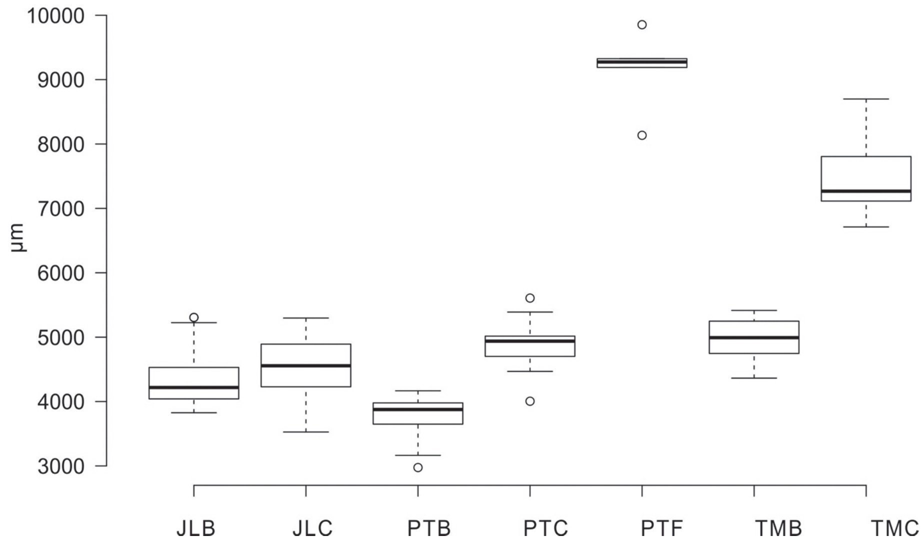

Figure 6. Wall thickness in the sample location. JLB – bowls thrown by Henry; JLC – conical vessels thrown by Henry; PTB – bowls thrown by Peter; PTC – conical vessels thrown by Peter; PTF – conical vessels thrown by Peter on a flywheel; TMB – bowls thrown by Thomas; TMC – conical vessels thrown by Thomas.

used wheel variants with a motorised flywheel which makes the regulation of rotation speed more difficult. Their performance is closer to kick wheels with characteristic speed oscillations. Thomas used a direct-drive wheel where the wheelhead is directly connected to the motor and speed is regulated by the foot pedal allowing maintenance of constant rotation speed. There were no apparent differences in their throwing styles with one slight exception which will be discussed later. Progress of wheel velocity during forming and time spent on manufacture was measured (Figure 8). Peter works significantly faster than the other two potters with lower wheel velocity (thus his work is the most efficient in terms of energy expenditure). The need for fewer moves to achieve the same shape is reflected by the low CSD in the tangential sections of samples taken from Peter's conical vessels compared to the other conical vessels. The bowls were generally thrown in a shorter time because of their smaller size. More interestingly, the velocity decreases more rapidly during the forming of bowls than of conical shapes. The wider shapes require more careful lifting to prevent disruption or collapse of the shape.

The effect of the shape is partially independent of an individual's throwing style and experience. The observed phenomena basically conform to the results of analysis of the second experimental collection: the more intricate the shape, the greater the transformation (or disruption of typical orientation). However, the effects vary from potter to potter. The distortion from typical wheel-throwing values for conical shapes could be hypothetically proportional to the degree of transformation from the roughout to the final shape. A roughout is formed in the first stage of throwing. In this stage, all the basic lifting of the clay mass is completed. Lifting causes development of the orientation patterns typical for wheel throwing. In the subsequent stage, the lifted clay mass is transformed into the required shape. This transformation is performed while the wheel is still spinning; pressure is combined with rotational energy, which theoretically causes (a) thinning of the vessel wall, (b) transformation of the object orientation resulting in lowering of the average angle (reorientation towards the horizontal axis) and an increase in CSD in the tangential section, and (c) greater parallel alignment of the objects to

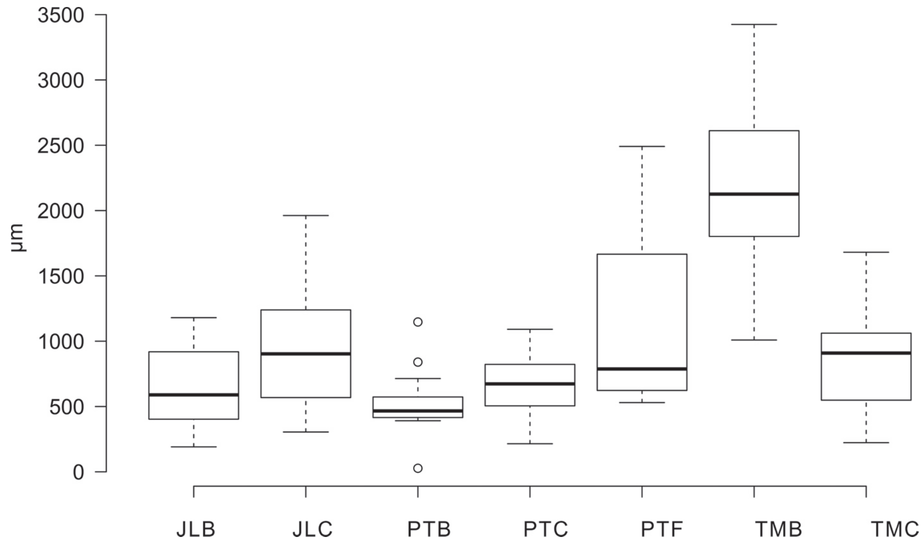

Figure 7. Difference in wall thickness in the sample location. JLB – bowls thrown by Henry; JLC – conical vessels thrown by Henry; PTB – bowls thrown by Peter; PTC – conical vessels thrown by Peter; PTF – conical vessels thrown by Peter on a flywheel; TMB – bowls thrown by Thomas; TMC – conical vessels thrown by Thomas.

the wall axis in perpendicular sections, *i.e.*, less profound imbrication patterns. However, there is another way to form more intricate shapes. For some potters, the distinction between the lifting of a roughout and its transformation into a final shape is rather theoretical. They continue lifting while forming the final shape and the two phases are not strictly separated. This approach is essential to achieving regular wall thickness. Consequently, in these cases, the orientation should not be strongly affected by the further transformation of the body.

All three potters involved in this experiment first throw the conical roughout and then widen it into the shape of a bowl. However, while Peter and Henry begin to widen the shape in the relatively early stage of the throwing, Thomas keeps the shape closed significantly longer. The potters demonstrate three different sets of effects, reflecting different throwing styles or skills. Peter's bowls are 23% thinner than his conical vessels (Figure 6). A significant increase in CSD in the tangential sections (Figure 4) was observed with a decrease in the inward inclination in the radial sections (Figure 5). On the other hand, the bowls show a similar deviation from the horizontal plane as the conical shapes (Figure 4). The thickness of Henry's bowls is similar to that of his conical vessels (Figure 6). There is no significant difference in object orientation in the tangential sections (neither in MD, nor in CSD), but Henry's bowls and conical vessels show the highest difference in inward inclination in the radial sections (Figure 5). Thomas's bowls are 34% thinner than his conical vessels (Figure 6) and the wall thickness is very uneven (Figure 7). Significantly lower deviation from the horizontal axis was observed, but no increase in CSD (Figure 4) and there is also no significant difference in orientation in the radial sections (Figure 5). None of the described patterns can be unequivocally related to the hypothetical effects of different throwing habits. For example, the lower deviation from the horizontal axis in the case of Thomas's bowls and the difference in thickness compared to conical vessels could be attributed to his habit of keeping the shape closed till the final stage of throwing, but there is no increase in CSD in tangential sections or decrease in imbrication pattern in radial sections.

The potter's experience is reflected indirectly by the deviation from the specified parameters of the experimental forming. The thicker walls of the conical shapes and uneven thickness of the bowl's walls testify to the fact that Thomas had difficulty achieving the required parameters. This corresponds with the observation (not exactly measured) that the shapes of Thomas's vessels visibly deviated from the template vessels. Thomas confirmed that, at the time of the experiment, he did not throw pottery regularly and intensively and consequently he lacked a corresponding routine. Also, the thickness of the conical vessels thrown on the flywheel reflects Peter's lack of familiarity with this type of wheel and probably also the technical problems associated with the device, causing unstable rotation. In both cases, lower deviation of the object orientation from the horizontal axis is characteristic. Consequently, this effect cannot be associated either with the vessel shape itself or with any other considered variables, *e.g.*, speed of the rotation.

The results of the analysis of this experimental dataset have significant consequences for the application of this methodology to archaeological pottery. The idea that the orientation pattern is consistent for wheel throwing in general (as for a forming method highly constrained by the forces employed during forming) irrespective of the potters' individual motor habits is no longer valid. The results show that we have to consider a wider range of the orientation values for wheel throwing and there is a partial overlap of values with combined forming methods. The measurements on tangential sections showing the deviation from a horizontal plane ranging between 15–35° and CSD 20–30° can be reliably interpreted as a result of wheel throwing. These intervals delimit the zone into which no data from other experimentally-tested forming methods have entered (Thér and Toms, 2016, Figure 6). However, CSD measurement results ranging between 30–40° cannot

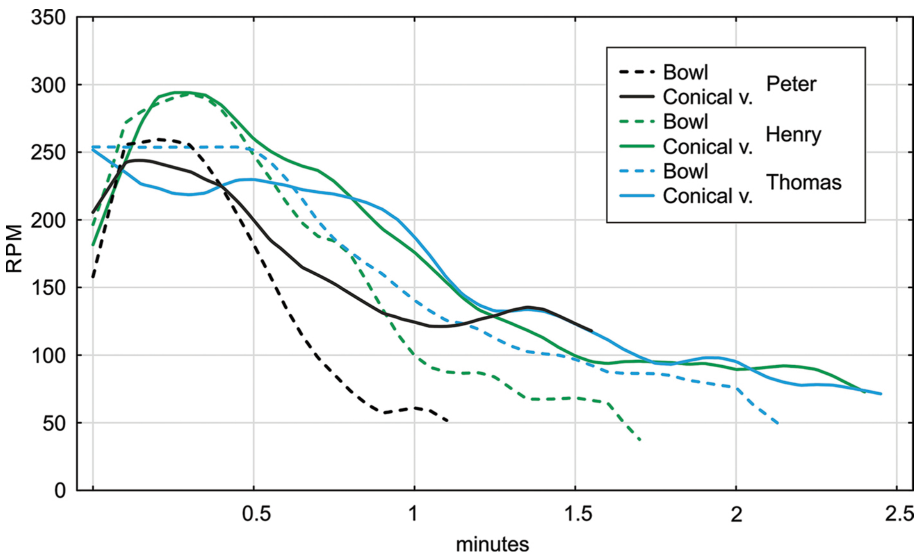

Figure 8. Averaged development of velocity of rotation of the wheels used by the potters in the experimental replication.

be interpreted unambiguously as they may reflect both an individual throwing style and combined techniques employing wheel shaping. In this case, evidence independent of orientation measurements is required to distinguish between the two variants of the potter's wheel contribution. Apart from traditional macrotrace analysis (Arnold, 1993; Choleva, 2012; Doherty, 2015; Dupont-Delaleuf, 2011; Gelbert, 1994; Jeffra, 2013; Knappett, 1999; Méry *et al.*, 2012; Roux, 2019; 1994; Roux and Courty, 1998; Rückl and Jacobs, 2016), which has limited value in that the technological context where the wheel-made pottery is made of fine-grained ceramic materials and the surface is carefully finished, we suggest combining two scales of structural analysis. The microscale imaging that reaches a resolution of a few micrometres can effectively capture an area of 2 cm^2, which is given by (a) the size of thin sections and the limitations in positioning planar tangential sections within curved vessel walls or (b) computed tomography limits in the combination of resolution and size of the samples. This type of analysis allows an accurate estimate of inclusion and void orientation, but only locally. We propose to combine microscale analysis with imaging at a smaller scale to capture a larger area of the sample. At this scale, the accurate measurement of orientation is complicated, especially when analysing fine-grained ceramics, but other structural features can be observed, especially structural discontinuities reflecting segmental forming techniques (Thér, 2020). By such a combination, the potential to differentiate individual techniques will be increased and, given the results of the described analysis, we can consider tracking the throwing (or more generally forming) style of potters based on structural analysis of their products. The most suitable technique for imaging the structure on a smaller scale seems to be computed tomography (Bernardini *et al.*, 2019; Gibbs, 2008; Gomart *et al.*, 2017; Kahl and Ramminger, 2012; Karl *et al.*, 2014; Kozatsas *et al.*, 2018; Kulkova and Kulkov, 2016; Machado *et al.*, 2013; Sanger *et al.*, 2013; Sanger, 2016).

5. Conclusion

Analysis of the experimental collection of pottery made by three professional potters using wheel throwing revealed imprints of individual motor habits captured by the orientation analysis. It draws attention to the significance of individual style or the specifics of individual motor habits in technological studies. The analysis demonstrates that the individual motor habits can significantly affect the orientational pattern even for a forming method that seems to be very deterministic in terms of the forces employed during forming. More attention must be paid in the future to identification and description of the diversity of the modalities of wheel throwing and subsequent determination of their effects in the archaeological record. This will help to define the limits of this forming method (and especially the limits of its effects observable in the archaeological record), which is crucial both for its distinction from other forming methods utilising rotational movement and for understanding the dynamics of the evolution of wheel throwing.

Acknowledgements

The research described in this paper was completed with support from the project "Technological changes in pottery manufacture in the context of social transformations during the La Tène period in Bohemia" (project 19-21146S), financed by the Czech Science Foundation. We would like to thank Madeleine Štulíková for her assistance in correcting the English grammar and to Ina Berg, Caroline Jeffra, and Chase A. M. Minos for their helpful comments.

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