Quantitative Morphological Analysis of Warp and Weft Yarns in Historical Woven Structures

Idelson, Antonio Iaccarino; Bergsma, Otto; Groves, Roger

DOI
10.1080/00393630.2025.2491250

Publication date
2025

Document Version
Final published version

Published in
Studies in Conservation

Studies in Conservation

ISSN: 0039-3630 (Print) 2047-0584 (Online) Journal homepage: www.tandfonline.com/journals/ysic20

Quantitative Morphological Analysis of Warp and Weft Yarns in Historical Woven Structures

Antonio Iaccarino Idelson, Otto Bergsma & Roger Groves

To cite this article: Antonio Iaccarino Idelson, Otto Bergsma & Roger Groves (05 Jun 2025): Quantitative Morphological Analysis of Warp and Weft Yarns in Historical Woven Structures, Studies in Conservation, DOI: 10.1080/00393630.2025.2491250

To link to this article: https://doi.org/10.1080/00393630.2025.2491250

Published online: 05 Jun 2025.

STUDIES IN CONSERVATION
https://doi.org/10.1080/00393630.2025.2491250

ORIGINAL RESEARCH OR TREATMENT PAPER

Quantitative Morphological Analysis of Warp and Weft Yarns in Historical Woven Structures

Antonio Iaccarino Idelson, Otto Bergsma and Roger Groves

Aerospace Engineering, Delft University of Technology, Delft, The Netherlands

ABSTRACT
This research presents a set of methods for obtaining measurable data on yarns in historical textiles, addressing a gap in conservation and conservation science. A systematic analysis was conducted on 26 specimens, primarily from historical paintings of known provenance, all including a selvedge. Techniques for measuring crimp, twist, yarn width and yarn thickness were developed. Methods for the measurement of thread count, fabric thickness, weight, and pH are also discussed. By quantifying these characteristics, this study enhances our understanding of traditional textile production. Numerical data enable direct comparisons between different fabric structures and allow correlations with the tensile properties of historical textiles. Correlations have been established between the measured characteristics of the interlaced yarns and the warp and weft directions, which appear to be uncontroversial within this group of samples. This improves the ability to distinguish warp and weft in a textile when a selvedge is not available. The set of methods is largely non-destructive, as only a few yarns need to be extracted to measure their crimp and thickness. The data needed for textile engineering research are made available for historical woven structures, providing new opportunities for their analysis and for predictive digital simulation. The next steps in this ongoing research are to explore correlations between the measured characteristics and the tensile response of the analysed textiles, and to extend the study to a wider range of historical fabrics to obtain more broadly representative data.

ARTICLE HISTORY
Received May 2024
Accepted April 2025

KEYWORDS
Warp; weft; thread count; yarn width; pH measurement; naturally aged canvas; twist; crimp; mechanical behaviour; canvas structure analysis

Introduction and general definitions

The structure and internal morphology of textiles are determined during their manufacture. A strand of fibre is spun into a yarn, and twisting gives it the cohesion and tensile strength needed for weaving. During the weaving process, the warp yarns are kept under tension on the loom and run parallel to the length of the fabric. They are divided into sets to create an open space, or shed, through which the weft runs before the warp sets are inverted to create a new shed. During weaving, the yarns intertwine and the resulting pressure changes their shape from straight to wavy. This waviness, or crimp, means that more yarn is needed to cover the distance between the edges of the fabric. The pressure also causes the cross-section of the yarn to change from roughly circular to elliptical, which is described by the length of the two axes, rather than simply a radius as before weaving. All these aspects are commonly quantified in textile industry research (Behera and Hari 2010; Neckář and Das 2018; Peirce 1937) allowing predictive models and structural comparisons between different fabrics. A comprehensive description of an industrial textile requires analysing the fibre composition, weave type, thickness, and weight per square meter. Additionally, the yarn density (thread count/cm), weight per unit length, twists per unit length, crimp percentage during weaving, and cross-sectional characteristics are examined.

Much less detailed data is available when it comes to historical canvas paintings supports, and textiles. This is due to the fact that it is not as easy to take samples from a historical artefact as it is from a new industrial product, and that a canvas support is typically impregnated with size and preparation layers or substances introduced by treatments. The only information usually available is the type of weave, the thread-count, and the nature of the fibres. The presence of paint layers and other contaminants even limits measurements of the weight per unit area and thickness of the textile. Most other measurements are complicated by the variability of historical materials and their limited availability for sampling. The weight of the yarn per unit length is a perfect example because clean yarns of sufficient length[1] are simply not available in conservation. The cross-section of historical yarns is very uneven along their length when compared to industrially spun yarns.

CONTACT Antonio Iaccarino Idelson iaccarino.a@gmail.com Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

The pH and the degree of polymerisation of the cellulose are sometimes measured in conservation science as indicators of degradation processes and, when available, can be used to support treatment decisions.

Twist and crimp measurements form a group of their own, as they are among the most relevant characteristics of a woven structure, and have always been the object of textile technology studies (Mertova, Neckar, and Muzaffar Ishtiaque 2016; Neckář and Das 2019; Peirce 1937). Detailed technological descriptions of ancient textiles, including measurements of twist and crimp, are rare. A rather exceptional case is Berry et al. (1978), which describes a rich archaeological find (more than 150 kg of raw textiles), that allowed for extensive sampling and invasive testing, making it possible to apply the textile engineering approaches to the measurement of twist, crimp, and even weight per unit length. Nevertheless, the elliptical yarn cross-section was characterised by the major axis alone (defined as the yarn diameter) and the minor axis was not mentioned. In Iaccarino Idelson, Bergsma, and Groves (2025), methods for measuring twist and crimp in historical textiles are described, which are part of the research presented in this paper.

The standard method of measuring twist in a yarn is to untwist it and count the number of turns required to revert the fibres to their original state, parallel to the yarn axis (Saville 1999). In general, the method is not applicable to historical textiles, because the yarns are either too fragile to withstand untwisting or impregnated with substances that would not allow it. Observation based methods (not requiring untwisting the yarn) are used to measure the 'twist angle', as described in handbooks (Seiler-Baldinger 1996), papers (Rouba 1992), archaeological reports (Ostergard 2004) and in studies dedicated to thread-by-thread tear mending (Flock 2020). However, the twist angle is a semi-qualitative value as the actual number of twists per meter in a yarn, obtained through the correlation of the angle with the width of the yarn, is not provided. A method that allows the correlation between the twist angle and the actual count of the twists per unit of length to be made (Conti and Tassinari 1973) has only recently been used in conservation science[2] (Iaccarino Idelson, Bergsma, and Groves 2025).

The standard method of measuring crimp is also mechanical, based on uncrimping the yarn by pulling it straight to calculate the difference in length (Kovar 2011), and is therefore not applicable to naturally aged or impregnated yarns. The path the yarn travels in the textile can be calculated by analysing its waveform in the cross section (see Figure 1) of the fabric (Mertova, Neckar, and Muzaffar Ishtiaque 2016) or by observing the image of individual yarns (Young and Jardine 2012), because geometric simplifications

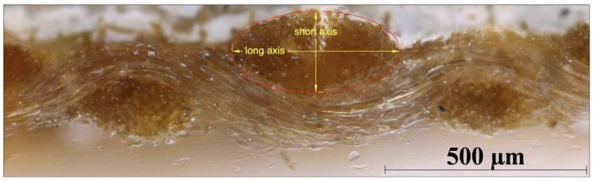

Figure 1. Typical elliptical cross-section of the yarns of a historical sample. Image: Giorgia Agresti.

provide reliable data for modern textiles, when they have a very constant waveform. An alternative optical method is based on drawing a line on the neutral axis of the yarn using specialised software (Kolcavova Sirkova and Vysanska 2012). This approach was found to be the most suitable for describing irregular crimp configurations and was used for the study of historical yarns (Iaccarino Idelson, Bergsma, and Groves 2025).

The most comprehensive descriptions to date of the canvas supports of paintings have been obtained from the analysis of X-ray images and provide information on the density, position, and direction of the yarns on the entire painting (Johnson, Johnson, and Erdmann 2013; Nobel et al. 2018; van de Wetering 1997). Such observations also allow the identification of warp and weft directions, based on the variability of the thread count, of the thread angle within the textile, and of the presence of specific irregularities in the weave, which are generally located in the weft. In the textile industry, automated methods have been developed to obtain the thread count from images of new textiles (Aldemir, Özdemir, and Sarı 2018; Pan et al. 2015). Although very useful for technical art history and for industrial inspection, none of these methods allows the measurement of the quantitative data that is the subject of the present research.

In conclusion, numerical data on crimp, twist, and yarn dimensions are lacking for historical textiles. However, such data are essential to establish correlations with their mechanical behaviour[3], to describe and compare different textiles, and to develop detailed finite element method (FEM) simulations.

Aim of the paper and research questions

The methodological study[4] reported here aims at a systematic approach to the morphological analysis of the woven structure of canvas painting supports with reference to textile engineering. The first research question is whether it is possible to obtain quantitative data on the woven structure of historical textiles. Such an opening would expand the possibilities for understanding their mechanical behaviour and improve the assessment of conservation conditions. Characteristics such as yarn dimensions, twist, crimp, and even thickness and weight/m^2, present specific difficulties when dealing with a sample that is highly variable, limited in quantity, degraded, and contaminated. The organisation of simple statistical methods for data collection is also a relevant subject, since the goal is to allow comparisons.

The second research question is whether it is possible to find recurring characteristics that can provide a degree of confidence in the identification of warp and weft yarns when a selvedge is not available. This seems to be a relatively urgent need, since the mechanical behaviour of the textile is different in the two directions (Young and Hibberd 1999), and their identification is relevant for conservation and research purposes (Rouba 1992; van de Wetering 1997; Johnson, Johnson, and Erdmann 2013; Nobel et al. 2018), as we will see in the literature outline.

Materials and methods

The group of samples, their preparation, and statistical data collection

A group of 'plain weave' fabrics[5] without paint layers was selected, all of which have a selvedge to ensure that warp and weft can be reliably identified. Most of the specimens (22 out of 26) are naturally aged, some with known provenance, date, and artist. These were extracted from paintings (dating from 1728 to the 1950s) during past conservation treatments, and 12 of them represent a relatively homogeneous group of mid-to-late nineteenth-century French artworks. Lining and loose lining canvases between the eighteenth and nineteenth centuries[6], and four modern canvases complete the set. Three of these are industrially woven lining canvases: two are typical open-weave paste-glue lining canvases, the Italian *patta* and *pattina*, from a 2015 lot; the basket weave canvas used in the making of a mock-up inspired to Rembrandt's *The Night Watch*; the 2021 manually woven proof of concept for the project[7] 'Canvassing the making', aiming to replicate a traditional canvas used by Dutch old masters, in which the same yarn was used for warp and weft. The complete list is in Table 1, also including their weight per square meter and pH, all provided as the mean of the values obtained on multiple samples from the same specimen. All specimens consist of single ply yarns, with a Z twist (Table 5).

Since all samples will be subjected to tensile tests, they were laser cut following the cruciform patterns described in Iaccarino Idelson et al. (2023). Laser cutting causes only a very localised burning of the yarns[8] while offering the considerable advantage of avoiding the mechanical stresses on the textile caused by any blade cutting method (see Figure 2). Laser cutting from a CAD drawing provides a precise and repeatable measure of the area of the sample, that was used to calculate the weight of the textile in grams/m^2. The sharp 10×10 mm testing area was photographed at high-resolution[9] and scaled to the real dimensions, to take precision measurements of the individual yarns with the support of a CAD[10] software. As a consistent area of observation is defined thanks to the CAD design of the laser cut[11], a weighted mean was calculated instead of a simple mean, after visually dividing the warp and weft yarns in three subsets for relative dimensions (small, medium, and

Table 1. General data on the samples, with the weight per square meter and pH.

		General data			Weight measures in grams							
	Specimen name	Date	Fibers	Manufacture	Sample 1	Sample 2	Sample 3	Sample 4	Mean	St. dev.	g/sqm	pH
1	plain canvas 1	18th c.	linen	hand	0.076	0.073	0.077	0.079	0.08	0.003	**257**	*6.5*
2	plain canvas 2	18th c.	linen	hand	0.130	0.129	0.134	0.125	0.13	0.004	**435**	*6.1*
3	plain canvas 3	18th c.	linen	hand	0.068	0.085	0.091	0.086	0.08	0.010	**278**	*6.4*
4	plain canvas 4	18th c.	hemp	hand	0.101	0.100	0.092	0.098	0.10	0.004	**329**	*7.4*
5	plain canvas 5	19th c.	hemp	hand	0.132	0.132	0.133	0.131	0.13	0.001	**445**	*7.3*
6	Domenico C. Malinconico	1728	hemp	hand	0.083	0.076	0.059	–	0.07	0.013	**244**	*6.2*
7	Bernard d'Agesci	1817	hemp	hand	0.151	0.126	0.048	0.071	0.10	0.048	**334**	*6.8*
8	medium paste lining canvas (IT)	early 19th c.	hemp	machine	0.055	0.047	0.051	0.044	0.05	0.005	**166**	*6.0*
9	heavy paste lining canvas (IT)	early 19th c.	linen	machine	0.179	0.189	0.193	–	0.19	0.007	**628**	*6.0*
10	Fragonard medium paste lining	mid 19th c.	hemp	machine	0.120	0.118	0.113	0.122	0.12	0.004	**397**	*6.1*
11	Raffaele Postiglione	1845	linen	hand	0.083	0.080	0.076	0.075	0.08	0.004	**265**	*5.2*
12	Alfred Dehodencq	1870	linen	machine	0.094	0.097	0.102	0.094	0.10	0.004	**326**	*5.6*
13	Jules Gélibert	1881	linen	machine	0.073	0.072	0.071	0.068	0.07	0.002	**238**	*5.8*
14	Louis Augustin Auguin	1885	linen	machine	0.088	0.091	0.085	0.089	0.09	0.003	**296**	*6.1*
15	Ludovic Alleaume	1887	linen	machine	0.072	0.074	0.073	0.076	0.07	0.002	**248**	*5.2*
16	Hubert Sauzeau 1	1893	linen	machine	0.058	0.065	0.060	0.060	0.06	0.003	**205**	*6.2*
17	Hubert Sauzeau 2	1898	hemp	machine	0.138	0.152	0.150	0.136	0.14	0.008	**485**	*6.6*
18	Charles Müller	late 19th c.	linen	machine	0.042	0.047	0.044	0.046	0.04	0.002	**150**	*5.6*
19	Furcy de Lavault	late 19th c.	linen	machine	0.067	0.066	0.072	0.066	0.07	0.003	**228**	*6.0*
20	Louis Alexandre Cabié	1905	weft hemp; warp cotton	machine	0.085	0.080	0.082	0.081	0.08	0.002	**276**	*5.9*
21	Louis Lessieux	early 20th c.	hemp	machine	0.068	0.054	0.052	0.061	0.06	0.007	**197**	*6.4*
22	Jeannine Gilles-Murique	mid 20th c.	hemp	machine	0.115	0.122	0.113	0.108	0.11	0.006	**385**	*5.5*
23	*Night Watch* mockup canvas	1975	linen	machine	0.097	0.096	0.101	0.096	0.10	0.002	**380**	*6.2*
24	*pattina* lining canvas	2015	linen	machine	0.043	0.043	0.047	0.045	0.04	0.002	**149**	*6.5*
25	*patta* lining canvas	2015	linen	machine	0.057	0.051	0.043	0.051	0.05	0.006	**171**	*6.6*
26	canvassing '03f'	2022	linen	hand	0.098	0.103	0.103	0.111	0.10	0.005	**349**	*7.8*

Figure 2. The image of one of the laser-cut samples (n. 2 in Table 1), with the indentations in the weft direction.

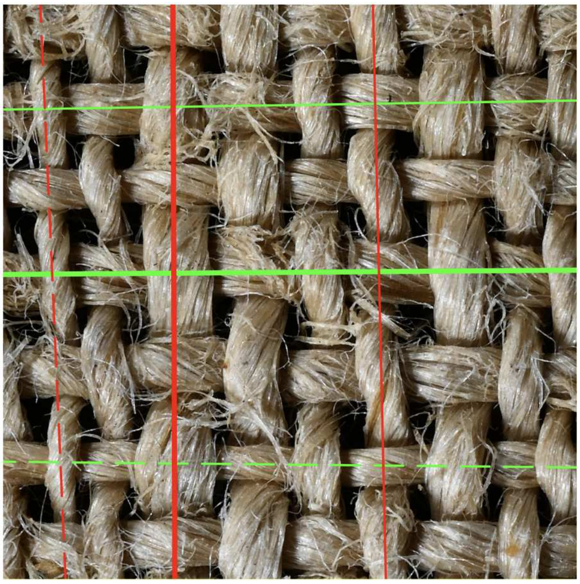

Figure 3. Example of the observations on the subsets. Yarns in warp (red) and weft (green) visually chosen to represent the small-medium-large subsets in the 1 cm^2 sample.

large). One yarn from each subset, chosen as the most representative, was measured at three locations using the procedure described in the next section. The mean value of the measures for the chosen yarn in each subset (Figure 3) was used to calculate the weighted mean. As this is the sum of the value obtained for each chosen yarn times the number of yarns in each subset, divided for the number of yarns in warp or weft, the process results in a matrix of 9 measures for warp and 9 for weft. This describes the value of the specific feature in each 1 cm^2 area of observation, and the standard deviation provides a measure of its variability.

Measuring procedures

Weight and thickness of the canvas, weight of the yarns, and thread-count

The samples were weighed[12] using a certified analytical scale[13] with a resolution of 0.1 mg and a repeatability of +/ – 0.05 mg. As the sample surface is a given information thanks to the laser-cutting procedure[14], a simple calculation provided the weight in g/m^2, averaging the weight of four samples.[15] The thickness of the canvas was measured using a 6 mm diameter flat-end micrometre with a resolution of 0.001 mm. The 'friction drive' was used, which slips when the set pressure is reached, allowing the spindle to stop moving even if the user continues to turn the thimble. The same, very low, compression force was applied on all samples.[16] Measurements were repeated at five points on each of the three selected samples. Since the length of the pieces of yarn that can be extracted from the specimens is not more than 20 or 30 mm, their weight happens to be too close to the lower limit of the analytical scale (0.1 mg). For this reason, after a few attempts with yarns from different specimens, it was decided to exclude this information from the set of data collected in this research. Thread-count in both directions was obtained visually under magnification at three locations in different samples. The information is correlated to each sample, and the general mean and standard deviation are given.

Identification of fibres

Individual fibres were extracted[17] from the yarn and mechanically separated using a specillum. A sample was prepared for observation under a mineralogical optical microscope using a microscope slide, Canada balsam, and a coverslip. The preparations thus obtained were observed under the Zeiss Axioskop polarising optical microscope with the Zeiss Axio Cam NRc camera attached, and the images were processed using Axio Vision processing software. The analysis of the morphological characteristics of the fibres was performed for comparison with databases in the literature (Markova 2019).

pH measurements

Measurement of the pH of an insoluble solid material requires bringing free ions into solution in order to quantify the H^+ concentration. Depending on the type of electrode chosen, it will either be immersed in the liquid phase or measure the pH of a thin liquid film on the surface of the solid. Immersion of the textile sample in the liquid phase is among the standard procedures for textiles[18], and although it involves the destruction of the sample, it was not ruled out as it could be performed after the tensile tests, which also damage the sample. However, preliminary tests showed that the pH value of the liquid phase remained unstable for a long time, probably due to the gradual solubilisation of materials in the historical canvas. This was even more pronounced when testing a canvas with preparation and paint layers. Consequently, the immersion method was not selected, as the results appeared too susceptible to unpredictable factors. A recently developed alternative method is to measure the pH of an agarose gel used to extract free ions from the surface (Rota et al. 2021), limiting the diffusion of water into the material. The method is extremely useful for fragile textiles[19] and is also used on paintings.[20] Nevertheless, after careful evaluation of the options, an intermediate approach was chosen, as in Böhme et al. (2020), based on the use of a contact pH meter with a drop of water placed on the sample.[21] The method used to be the standard approach before the introduction of the agarose gels, and has been successfully used on canvas paintings over the past decade.[22] The advantage is that it seems to allow the extraction of more ions from below the surface if compared with the agarose gel, thus providing values with a wider distribution. If compared with the method based on the immersion of the sample, the pH value stabilises within 3–5 min, and values appeared to be more repeatable. Of course, the problem is not one offering a single solution, and all methods currently used in conservation practice and conservation science offer advantages and limitations.

Yarn width assessment

The long axis of the elliptical cross-section of the yarns (see Figure 1) can be measured by a completely non-destructive observation of the surface of the textile.[23] Free access to a large number of measuring points allows the weighted mean to be calculated. As previously mentioned, within the 1 cm^2 area of the digital image, the yarns were grouped in the three subsets in warp and three in weft (Figure 3). A representative yarn in each subset was identified and measured at three different locations, by tracing the tangent on the side of the yarn, then offset to the opposite side including its width (lines 1 and 2 in Figure 4). Measuring the short axis of the elliptical cross-section (Figure 1) requires extracting the yarns from the textile to observe them from the side. As the same destructive operation was necessary to measure the crimp value, both measurements were carried out on the same yarns.

Twist measures

Twist measurements are taken on the same yarns and at the same locations as those selected for the width measurements. A diagonal line is drawn (line 4, in Figure 4) following the direction of the twisted fibres visible on the surface, as when measuring the 'twist angle' (Seiler-Baldinger 1996); the adjacent perpendicular segment, line 3, drawn at the intersection between lines 4 and 2, represents the yarn width and closes a right-angle triangle in which the second cathetus is named '*L*'. The length of *L* (in mm) is used to calculate the twists per meter (TPM) at a given point on the yarn according to the simple equation: **TPM = 318/*L***. For a complete description and demonstration, see Conti and Tassinari (1973) or its English translation [https://doi.org/10.5281/zenodo.13949377]. The method was applied to 11 textiles and further validated in Iaccarino Idelson, Bergsma, and Groves (2025). The twist direction (Z or S) was recorded, and the weighted mean of the TPM and the standard deviation was calculated.

Crimp measures and yarn thickness

The procedure requires the extraction of three yarn fragments in both warp and weft, which are photographed in high resolution and scaled to their real dimensions in CAD. The polyline ***P*** (Figure 5) is drawn in the middle of the yarn along its neutral axis, and the straight-line ***T***, connecting its ends along the plane of the textile, is used to calculate the crimp % according to the standard equation (1).

$$\text{Crimp }\% = \frac{P - T}{P}\ x\ 100 \qquad (1)$$

Measuring crimp on the same yarns used for width and twist measurements would require completely disassembling the textile sample. Since this would result in losing the correlation with the sample's mechanical behaviour under tensile testing, neighbouring yarns from the textile around the laser-cut perimeter were used instead.

The available yarns were 8–25 mm long, thus providing a value that represents the mean of the waveform along their path. The mean and the standard deviation were calculated. A more detailed description of the crimp measurement method including a further level of validation, based on Kovar (2011) and Mertova, Neckar, and Muzaffar Ishtiaque (2016), is in Iaccarino Idelson, Bergsma, and Groves (2025).

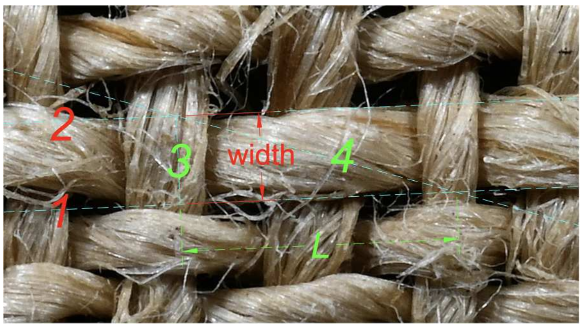

Figure 4. The geometries used to measure yarn width (lines 1, 2) and twist (lines 3, 4 and segment L).

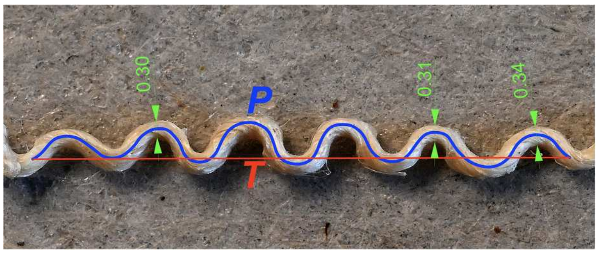

Figure 5. The geometry involved in the measures of crimp (lines P and T) and of yarn thickness.

The image in Figure 5 shows a yarn along the z axis, orthogonal to the (x-y) plane of the textile seen in Figure 4. The z axis image is necessary to measure the, otherwise invisible, thickness of the yarns. Using similar CAD procedures, at least three thickness measurements were taken from each of the same yarns used to calculate the crimp. The mean and the standard deviation of at least nine measurements of the yarn thickness in warp and nine in weft were calculated.

Experimental results

Weight and thickness of the canvas, thread-count, fibre identification, and pH

The weight of the samples, their mean, and standard deviation are found in Table 1, along with the nature of the fibres and measured pH. The thickness of the canvas samples was measured at five points in four units, and the general mean values of the 20 measurements and their standard deviation are given in Table 2. The number of yarns per cm was counted at three locations, in different samples. The general mean values of the readings and their standard deviation are listed in Table 3.

The mean values in warp and weft are compared in Figure 6, and the difference between the two values is also shown in the histogram. The warp yarns are more numerous than the weft yarns in 20 of the 26 specimens (77%), and the remaining six have equal values. This correlation is due to practical considerations on the part of the manufacturer to achieve a balanced textile. As the main cost in the weaving process is the casting of the wefts in the shed, it is preferable to use a higher number of warp yarns to achieve a given density in a plain weave textile. In addition, a high weft density produces more tension in the warp, which will unbalance the fabric and cause it to wear out faster in use.[24] A higher thread count in the warp direction is confirmed in most textile engineering literature, as in Pan et al. (2015).

Yarn width and thickness

The width of the yarns was measured using the geometries described in Figure 4, according to the relative dimensional subsets (see Figure 3) in the 1 cm^2 image of the sample. The data in Table 4 describe the variability of the yarns observed in the samples. When the number of the yarns of the middle subset (M) prevails on the others (as in nos 13; 20; 26 in the warp and in nos 13; 22; 24 in the weft), the textile has a high dimensional homogeneity. If the S and L subsets represent a higher share of the population, yarn dimensions are more variable. A further evaluation of the variability can be obtained by comparing the measurements in the subsets, using the standard deviation. Specimen n. 10 serves as a useful example, as the number of yarns in the M subset is predominant. However, in the warp, the S value is nearly four times smaller than the L, resulting in a high standard deviation (0.3 mm).

The standard deviation of the width values measured in warp and weft (Table 4) allows a comparison to be made with the higher variability of the weft yarn width found the literature (Johnson, Johnson, and Erdmann 2013; Nobel et al. 2018; Rouba 1992; van de Wetering 1997). However, the similarity of the mean standard deviation values in the warp (0.17 mm) and weft (0.15 mm), along with their close standard deviations (0.07 mm in warp and 0.08 mm in weft) prevents robust conclusions from being drawn within the current sample set. The standard deviation of the difference between the L and S width values in Table 5 is diverges slightly more in warp (0.11 mm) and in weft (0.14 mm). When the number of the observed samples will be larger, in a future phase of the research, other statistical approaches will be possible.

The weighted mean of the width values in warp and in weft are compared in Figure 7, where the difference between the two values is also shown. In the large majority of cases (20 out of 26, or 77%) the warp yarns are wider than the weft yarns. In the 11 cases under the pale blue band in Figure 7, the differences are very shallow: between 0.08 mm and – 0.08 mm. If this subset is not included in the general evaluation, the remaining 15 values show more substantial differences (ranging from 13% to 58% of the width). Among these, warp yarns are wider in 12 textiles, while the opposite is true in only in 3 cases, showing a slightly higher prevalence (80%).

In Figure 8 the thickness of the yarns in the two directions is compared, and we see that in 19 cases out of 26 (73%) the weft yarns are thicker than the warp, despite their lower width. If the subset under the pale blue band is not included (filtering the differences between 0.02 and – 0.02 mm), the prevalence becomes 67% (10 over 15 textiles). This apparently surprising information further confirms the role of twist in preserving the original circular shape of the yarn, as the weft yarns exhibit a higher TPM value.

In Figure 9 the elliptical cross-sectional area of the yarns is plotted, and shows a slight prevalence of the

Table 2. The thickness of the canvas samples.

		Textile thickness measurements (mm)					
Specimen name		Sample 1	Sample 2	Sample 3	Sample 4	mm	St. dev.
1	plain canvas 1	0.52	0.59	0.52	0.55	**0.54**	0.03
2	plain canvas 2	1.01	0.98	1.00	0.92	**0.98**	0.04
3	plain canvas 3	0.36	0.37	0.32	0.36	**0.35**	0.02
4	plain canvas 4	0.83	0.82	0.84	0.87	**0.84**	0.02
5	plain canvas 5	0.87	0.88	0.86	0.87	**0.87**	0.01
6	Domenico C. Malinconico	0.25	0.27	0.27	0.27	**0.26**	0.01
7	Bernard d'Agesci	0.47	0.38	0.39	0.38	**0.41**	0.04
8	medium paste lining canvas (IT)	0.49	0.49	0.47	0.48	**0.48**	0.01
9	heavy paste lining canvas (IT)	1.32	1.21	1.32	1.28	**1.28**	0.05
10	Fragonard medium paste lining	0.68	0.65	0.72	0.69	**0.68**	0.03
11	Raffaele Postiglione	0.77	0.58	0.62	0.66	**0.66**	0.08
12	Alfred Dehodencq	0.35	0.33	0.29	0.33	**0.32**	0.03
13	Jules Gélibert	0.47	0.45	0.46	0.44	**0.45**	0.01
14	Louis Augustin Auguin	0.22	0.22	0.22	0.21	**0.22**	0.01
15	Ludovic Alleaume	0.44	0.44	0.46	0.44	**0.44**	0.01
16	Hubert Sauzeau 1	0.38	0.38	0.37	0.38	**0.37**	0.00
17	Hubert Sauzeau 2	0.78	0.82	0.85	0.80	**0.81**	0.03
18	Charles Müller	0.25	0.27	0.27	0.27	**0.26**	0.01
19	Furcy de Lavault	0.38	0.38	0.39	0.37	**0.38**	0.01
20	Louis Alexandre Cabié	0.28	0.28	0.27	0.29	**0.28**	0.01
21	Louis Lessieux	0.18	0.18	0.20	0.24	**0.20**	0.03
22	Jeannine Gilles-Murique	0.80	0.85	0.79	0.75	**0.80**	0.04
23	*Night Watch* mockup canvas	0.72	0.71	0.72	0.72	**0.72**	0.00
24	*pattina* lining canvas	0.45	0.43	0.43	0.44	**0.44**	0.01
25	*patta* lining canvas	0.60	0.56	0.51	0.57	**0.56**	0.04
26	canvassing '03f'	0.78	0.82	0.82	0.81	**0.81**	0.02

warp (15 over 11, or 58%). Filtering the differences between 0.016 and -0.016 mm^2, the prevalence of the warp is reduced to 54%. This suggests the hypothesis that the yarns were originally only slightly different in the two directions and that the larger width value of the warp yarns is acquired during weaving and related to the higher crimp. Still, the differences in twist (a value unaffected by the weaving process) support the hypothesis of an intentional choice of larger yarns for the warp direction. The correlation between twist values and yarn dimensions will be further explored in the next section.

Twist per meter

The amount of twist that natural fibres undergo during the spinning process depends on the characteristics of the fibre strand, which are highly variable (Kania 2013). Thinner fibre strands twist more than a bulkier flock, stiffer sections twist less, resulting in variations in twist and width along the yarn's length. 'Twist goes where the yarns are thinner', as a traditional spinner would say, and the correlation between TPM and yarn linear density is well established in textile engineering (Saville 99; Neckář and

Table 3. Thread count analysis.

		Thread count									
Specimen name		warp 1	warp 2	warp 3	weft 1	weft 2	weft 3	warp mean	weft mean	warp st. dev.	weft st. dev.
1	plain canvas 1	16.0	17.0	17.0	13.5	14.0	13.0	**16.7**	**13.5**	**0.6**	**0.5**
2	plain canvas 2	12.0	11.0	10.0	8.0	8.0	8.0	**11.0**	**8.0**	**1.0**	**0.0**
3	plain canvas 3	14.0	13.0	14.0	12.0	12.0	12.0	**13.7**	**12.0**	**0.6**	**0.0**
4	plain canvas 4	9.0	9.0	9.0	7.0	7.0	7.0	**9.0**	**7.0**	**0.0**	**0.0**
5	plain canvas 5	17.5	16.0	16.0	11.0	10.0	12.0	**16.5**	**11.0**	**0.9**	**1.0**
6	Domenico C. Malinconico	13.0	13.0	13.0	13.0	13.0	13.0	**13.0**	**13.0**	**0.0**	**0.0**
7	Bernard d'Agesci	19.0	19.0	18.0	15.5	17.5	18.0	**18.7**	**17.0**	**0.6**	**1.3**
8	medium paste lining canvas (IT)	8.0	7.0	8.0	8.0	7.0	8.0	**7.7**	**7.7**	**0.6**	**0.6**
9	heavy paste lining canvas (IT)	9.0	8.5	8.5	7.0	7.0	7.0	**8.7**	**7.0**	**0.3**	**0.0**
10	Fragonard medium paste lining	14.0	14.0	13.0	11.0	12.0	11.0	**13.7**	**11.3**	**0.6**	**0.6**
11	Raffaele Postiglione	8.0	8.0	8.0	8.0	8.0	8.0	**8.0**	**8.0**	**0.0**	**0.0**
12	Alfred Dehodencq	17.0	17.0	17.0	11.0	11.0	11.0	**17.0**	**11.0**	**0.0**	**0.0**
13	Jules Gélibert	24.0	24.0	24.0	19.0	19.0	18.0	**24.0**	**18.7**	**0.0**	**0.6**
14	Louis Augustin Auguin	26.0	24.0	26.0	26.0	24.0	25.0	**25.3**	**25.0**	**1.2**	**1.0**
15	Ludovic Alleaume	23.0	25.0	24.0	21.0	22.0	22.0	**24.0**	**21.7**	**1.0**	**0.6**
16	Hubert Sauzeau 1	22.0	22.0	22.0	19.0	21.0	20.0	**22.0**	**20.0**	**0.0**	**1.0**
17	Hubert Sauzeau 2	14.0	14.0	14.0	12.0	12.0	12.0	**14.0**	**12.0**	**0.0**	**0.0**
18	Charles Müller	32.0	32.0	30.0	29.0	29.0	29.0	**31.3**	**29.0**	**1.2**	**0.0**
19	Furcy de Lavault	23.5	24.0	23.0	23.0	22.0	22.0	**23.5**	**22.3**	**0.5**	**0.6**
20	Louis Alexandre Cabié	11.0	12.0	12.0	10.5	11.0	11.0	**11.7**	**10.8**	**0.6**	**0.3**
21	Louis Lessieux	21.0	21.0	21.0	21.0	21.0	21.0	**21.0**	**21.0**	**0.0**	**0.0**
22	Jeannine Gilles-Murique	8.0	8.0	8.0	8.0	8.0	8.0	**8.0**	**8.0**	**0.0**	**0.0**
23	*Night Watch* mockup canvas	20.0	21.0	19.0	15.0	16.0	17.0	**20.0**	**16.0**	**1.0**	**1.0**
24	*pattina* lining canvas	9.0	9.0	9.0	9.0	9.0	9.0	**9.0**	**9.0**	**0.0**	**0.0**
25	*patta* lining canvas	7.0	7.0	7.0	5.0	5.0	5.0	**7.0**	**5.0**	**0.0**	**0.0**
26	canvassing '03f'	12.0	12.0	12.0	7.0	7.0	7.0	**12.0**	**7.0**	**0.0**	**0.0**

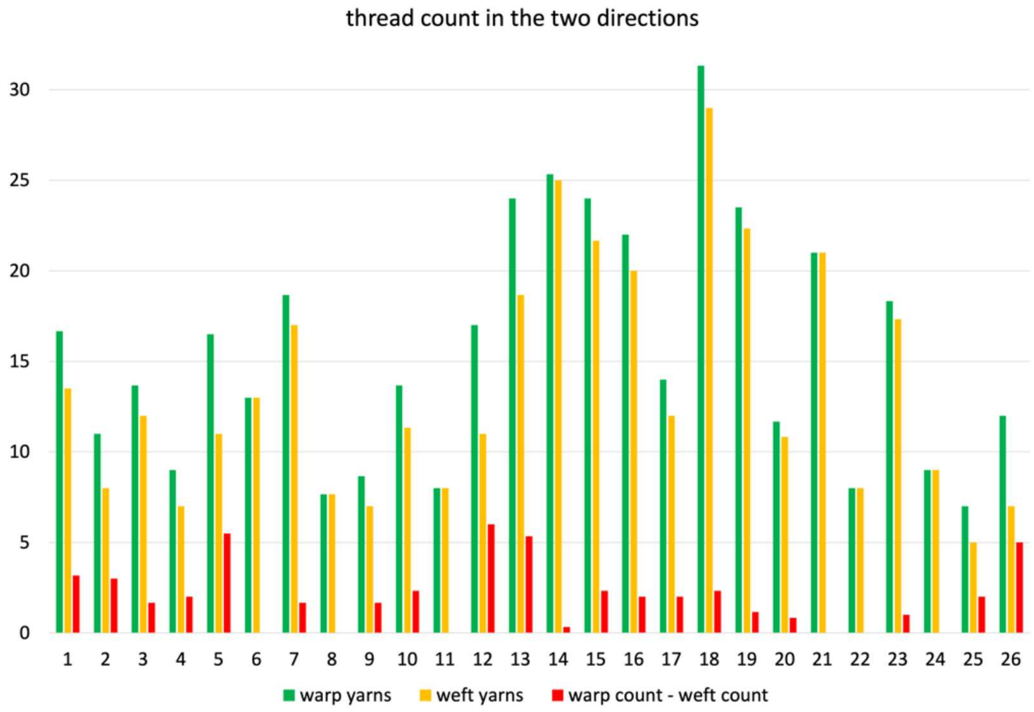

Figure 6. Thread-count in the two directions. Warp yarns are more numerous than weft yarns in 77% of the textiles, or equal.

Das 2018). Table 5 presents data analysing the relationship existing between yarn width and TPM, highlighting the differences across the dimensional subsets of yarns. The width and TPM value of each yarn were measured at the same location, and each of the values in Table 5 is the mean of three locations on the same yarn. Within the area of observation in the samples, the thinner yarns (class S) consistently exhibit a higher TPM value, while the wider yarns (Class L) show a lower one. Their difference is always a positive number, and the % difference in TPM is correlated to the % difference measured in the yarn width.

Table 6 presents the yarn width and TPM values in warp and weft, explaining why the weft yarns have a higher TPM value, as they are often thinner. A correlation similar to that seen in Figure 6 for the higher yarn width in the warp (80%) might be expected. However, a weaker correlation is found, with only 17 out of 26 cases (65%) showing this trend. Notably, in five of the nine cases where the TPM is higher in the warp yarns, this results from the warp being thinner than the weft. Additionally, these specimens have other unusual morphological characteristics: n. 8 and n. 24 are very open-weave canvases used for lining, with yarns of equal width and thickness in both directions; n. 20 and n. 22 are more recent historical textiles (n. 20 has a thinner cotton warp and thicker hemp weft), both apparently designed for painting, with closely spaced flat yarns and a high cover factor.

The degree of yarn compression (defined as the width-to-thickness ratio) appears to be directly correlated with the amount of twist in the yarns. This is illustrated in Figure 10, where the z axis compression is compared with TPM. A higher twist means better cohesion of the yarn and higher friction between the fibres, both implying a higher retention of the original circular section. As a result, weft yarns generally experience less compression along the z-axis than warp yarns (86%).

Crimp % value

The crimp values in warp and weft, illustrated in Table 7 and in Figure 11, provide rather uncontroversial evidence of the prevalence of crimp in the warp direction in our specimens, with higher values in 24 out of 26 cases. Filtering the +/ − 0.5% differences, the prevalence of the warp is increased to 96% (23 over 24 textiles). Warp crimp is on average 50% higher than weft crimp, exceeding 64% in 10 cases and less than 23% in only one case. The reason for such a large difference is that the weft yarn inserted between the warps causes them to bend during the shedding process, creating a crimped shape that becomes permanent in the woven canvas. Such a crimped shape is maintained by the friction and internal tensions between the yarns. As it is usually reduced after wetting and/or stretching of the fabric, we can assume that the crimp values in the historical textiles studied here were probably higher at the origin.

Specimen 26, hand woven from the same yarn bobbin in warp and weft, exhibits nearly identical TPM in the two directions (Tables 5 and 6), and so is the z axis compression (Figure 10). The variability in yarn width and thickness appears to stem from the inherent characteristics of the yarn itself. However,

Table 4. The relative dimension subsets, the mean values and the weighted mean of the yarn width observations; the thickness of the yarns, their mean, and standard deviation values.

WARP yarn width		Dimensional classes numerosity				Yarn width means					Yarn thickness				
Specimen name		th. count	S	M	L	S mean	M mean	L mean	w. mean	*st. dev.*	Mean 1	Mean 2	Mean 3	Warp	*St. dev.*
1	plain canvas 1	**16.7**	4	7.7	5	0.30	0.43	0.67	**0.47**	*0.16*	0.22	0.17	0.22	**0.20**	*0.03*
2	plain canvas 2	**11.0**	1	7.0	3	0.56	0.79	1.17	**0.87**	*0.28*	0.37	0.24	0.38	**0.33**	*0.08*
3	plain canvas 3	**13.7**	1	9.7	3	0.53	0.87	1.00	**0.87**	*0.21*	0.31	0.27	0.25	**0.28**	*0.03*
4	plain canvas 4	**9.0**	2	5.0	2	0.53	0.76	1.16	**0.80**	*0.28*	0.46	0.59	0.41	**0.49**	*0.09*
5	plain canvas 5	**16.5**	3	8.5	5	0.39	0.59	0.87	**0.64**	*0.21*	0.25	0.24	0.33	**0.27**	*0.05*
6	Domenico C. Malinconico	**13.0**	2	7.0	4	0.43	0.72	0.80	**0.70**	*0.19*	0.28	0.22	0.23	**0.24**	*0.03*
7	Bernard d'Agesci	**18.7**	1	13.7	4	0.28	0.34	0.58	**0.39**	*0.15*	0.21	0.28	0.31	**0.27**	*0.05*
8	medium paste lining canvas (IT)	**7.0**	2	3.0	2	0.62	0.70	1.11	**0.79**	*0.24*	0.39	0.31	0.39	**0.36**	*0.05*
9	heavy paste lining canvas (IT)	**8.7**	1	5.7	2	0.81	1.18	1.39	**1.19**	*0.25*	0.50	0.52	–	**0.51**	*0.01*
10	Fragonard medium paste lining	**13.7**	1	10.7	2	0.23	0.74	0.88	**0.72**	*0.30*	0.33	0.23	0.34	**0.30**	*0.06*
11	Raffaele Postiglione	**8.0**	1	6.0	1	0.41	0.61	0.76	**0.60**	*0.16*	0.34	0.38	0.43	**0.38**	*0.05*
12	Alfred Dehodencq	**17.0**	2	12.0	3	0.47	0.69	0.94	**0.71**	*0.20*	0.33	0.37	0.44	**0.38**	*0.06*
13	Jules Gélibert	**24.0**	1	22.0	1	0.40	0.49	0.53	**0.49**	*0.09*	0.21	0.20	0.20	**0.20**	*0.01*
14	Louis Augustin Auguin	**25.0**	2	21.0	2	0.33	0.38	0.50	**0.39**	*0.10*	0.28	0.23	0.21	**0.24**	*0.04*
15	Ludovic Alleaume	**24.0**	2	18.0	4	0.30	0.43	0.54	**0.44**	*0.11*	0.15	0.18	0.16	**0.16**	*0.02*
16	Hubert Sauzeau 1	**22.0**	3	15.0	4	0.38	0.49	0.54	**0.48**	*0.07*	0.21	0.20	0.28	**0.23**	*0.04*
17	Hubert Sauzeau 2	**14.0**	2	7.0	5	0.58	0.77	0.85	**0.77**	*0.13*	0.29	0.30	0.38	**0.32**	*0.05*
18	Charles Müller	**31.3**	5	20.3	6	0.27	0.34	0.44	**0.35**	*0.07*	0.15	0.16	0.11	**0.14**	*0.03*
19	Furcy de Lavault	**23.5**	2	14.5	7	0.32	0.42	0.66	**0.48**	*0.16*	0.18	0.18	0.15	**0.17**	*0.02*
20	Louis Alexandre Cabié	**11.7**	1	9.7	1	0.62	0.72	0.96	**0.73**	*0.16*	0.40	0.33	0.42	**0.38**	*0.05*
21	Louis Lessieux	**21.0**	4	12.0	5	0.37	0.46	0.61	**0.48**	*0.11*	0.15	0.15	0.13	**0.14**	*0.01*
22	Jeannine Gilles-Murique	**8.0**	2	5.0	1	0.95	1.03	1.57	**1.08**	*0.31*	0.33	0.37	0.40	**0.37**	*0.04*
23	*Night Watch* mockup canvas	**19.3**	2	14.3	3	0.41	0.72	0.74	**0.69**	*0.16*	0.28	0.27	0.27	**0.27**	*0.01*
24	*pattina* lining canvas	**9.0**	2	6.0	1	0.37	0.42	0.51	**0.42**	*0.07*	0.37	0.31	0.24	**0.31**	*0.07*
25	*patta* lining canvas	**7.0**	1	3.0	3	0.54	0.76	0.94	**0.81**	*0.17*	0.33	0.39	0.39	**0.37**	*0.03*
26	canvassing '03f'	**12.0**	1	9.0	2	0.62	0.71	0.85	**0.73**	*0.13*	0.46	0.54	0.50	**0.50**	*0.04*
WEFT yarn width		Dimensional classes numerosity				Yarn width means					Yarn thickness				
Specimen name		th. count	S	M	L	S mean	M mean	L mean	w. mean	*st. dev.*	Mean 1	Mean 2	Mean 3	weft	*St. dev.*
1	plain canvas 1	**13.5**	3	5.5	5	0.38	0.41	0.55	**0.46**	*0.08*	0.23	0.24	0.20	**0.22**	*0.02*
2	plain canvas 2	**8.0**	1	6.0	1	0.58	0.71	1.13	**0.75**	*0.26*	0.32	0.41	0.50	**0.41**	*0.09*
3	plain canvas 3	**12.0**	1	9.0	2	0.36	0.59	0.98	**0.64**	*0.28*	0.46	0.45	-	**0.46**	*0.01*
4	plain canvas 4	**7.0**	1	4.0	2	0.67	0.97	1.11	**0.97**	*0.21*	0.48	0.48	0.36	**0.44**	*0.07*
5	plain canvas 5	**11.0**	2	7.0	2	0.47	0.59	0.77	**0.60**	*0.13*	0.44	0.43	0.52	**0.46**	*0.05*
6	Domenico C. Malinconico	**13.3**	3	6.3	4	0.32	0.50	0.57	**0.48**	*0.12*	0.22	0.28	0.29	**0.26**	*0.04*
7	Bernard d'Agesci	**17.0**	2	10.0	5	0.27	0.48	0.50	**0.46**	*0.11*	0.18	0.18	0.21	**0.19**	*0.02*
8	medium paste lining canvas (IT)	**8.0**	2	4.0	2	0.53	0.79	0.97	**0.77**	*0.21*	0.30	0.23	0.46	**0.33**	*0.12*
9	heavy paste lining canvas (IT)	**7.0**	1	5.0	1	0.47	0.81	0.81	**0.76**	*0.17*	0.48	0.56	-	**0.52**	*0.06*
10	Fragonard medium paste lining	**11.3**	1	7.3	3	0.33	0.73	0.76	**0.70**	*0.21*	0.28	0.33	0.29	**0.30**	*0.03*
11	Raffaele Postiglione	**8.0**	1	5.0	2	0.54	0.97	1.12	**0.96**	*0.27*	0.40	0.34	0.37	**0.37**	*0.03*
12	Alfred Dehodencq	**11.0**	2	7.0	2	0.32	0.54	0.62	**0.51**	*0.14*	0.28	0.35	0.33	**0.32**	*0.04*
13	Jules Gélibert	**18.7**	1	16.7	1	0.34	0.40	0.53	**0.41**	*0.10*	0.22	0.22	0.24	**0.23**	*0.01*
14	Louis Augustin Auguin	**25.3**	2	21.3	2	0.31	0.32	0.46	**0.33**	*0.07*	0.31	0.28	0.29	**0.29**	*0.02*
15	Ludovic Alleaume	**21.7**	2	16.7	3	0.28	0.34	0.40	**0.35**	*0.06*	0.16	0.16	0.18	**0.17**	*0.01*
16	Hubert Sauzeau 1	**20.0**	3	14.0	3	0.37	0.41	0.40	**0.40**	*0.05*	0.23	0.23	0.24	**0.23**	*0.01*
17	Hubert Sauzeau 2	**12.0**	2	8.0	2	0.50	0.46	0.63	**0.50**	*0.08*	0.32	0.33	0.39	**0.35**	*0.04*
18	Charles Müller	**29.0**	5	20.0	4	0.19	0.31	0.40	**0.30**	*0.09*	0.11	0.16	0.14	**0.14**	*0.03*
19	Furcy de Lavault	**22.3**	4	12.3	6	0.24	0.34	0.49	**0.36**	*0.12*	0.18	0.17	0.30	**0.22**	*0.07*
20	Louis Alexandre Cabié	**10.8**	2	5.8	3	0.61	0.71	1.18	**0.82**	*0.27*	0.43	0.44	0.56	**0.48**	*0.07*
21	Louis Lessieux	**21.0**	7	12.0	2	0.24	0.29	0.42	**0.29**	*0.09*	0.22	0.17	0.13	**0.17**	*0.05*
22	Jeannine Gilles-Murique	**8.0**	1	6.0	1	1.11	1.06	1.64	**1.14**	*0.31*	0.47	0.45	0.44	**0.45**	*0.02*
23	*Night Watch* mockup canvas	**17.3**	3	11.3	3	0.49	0.45	0.51	**0.46**	*0.03*	0.31	0.32	0.31	**0.31**	*0.01*
24	*pattina* lining canvas	**9.0**	1	7.0	1	0.27	0.47	0.58	**0.46**	*0.14*	0.38	0.30	0.27	**0.32**	*0.06*
25	*patta* lining canvas	**5.0**	1	2.0	2	0.60	0.76	0.87	**0.77**	*0.13*	0.41	0.36	0.47	**0.41**	*0.06*
26	canvassing '03f'	**7.0**	1	5.0	1	0.61	0.66	0.79	**0.67**	*0.08*	0.47	0.42	0.48	**0.46**	*0.03*

Table 5. Warp and weft Twist Per Meter as function of the yarn width.

WARP		Warp yarn width				Warp TPM				Twist
Specimen name		Small	Medium	Large	% Large-Small	Small	Medium	Large	% Small-Large	Z or S
1	plain canvas 1	0.30	0.43	0.67	**55%**	374.89	264.12	218.77	**42%**	Z
2	plain canvas 2	0.56	0.79	1.17	**52%**	304.32	115.02	145.29	**52%**	Z
3	plain canvas 3	0.53	0.87	1.00	**47%**	298.24	143.08	124.82	**58%**	Z
4	plain canvas 4	0.53	0.76	1.16	**54%**	291.42	190.29	101.61	**65%**	Z
5	plain canvas 5	0.39	0.59	0.87	**55%**	321.07	335.95	180.68	**44%**	Z
6	Domenico C. Malinconico	0.43	0.72	0.80	**46%**	438.67	144.33	134.33	**69%**	Z
7	Bernard d'Agesci	0.28	0.34	0.58	**51%**	515.59	184.70	173.96	**66%**	Z
8	medium paste lining canvas (IT)	0.62	0.70	1.11	**44%**	318.98	235.03	136.80	**57%**	Z
9	heavy paste lining canvas (IT)	0.81	1.18	1.39	**42%**	180.63	224.10	115.18	**36%**	Z
10	Fragonard medium paste lining	0.23	0.74	0.88	**74%**	394.21	186.25	153.44	**61%**	Z
11	Raffaele Postiglione	0.41	0.61	0.76	**46%**	310.29	221.07	196.94	**37%**	Z
12	Alfred Dehodencq	0.47	0.69	0.94	**50%**	253.23	150.43	158.78	**37%**	Z
13	Jules Gélibert	0.40	0.49	0.53	**24%**	280.13	244.90	193.09	**31%**	Z
14	Louis Augustin Auguin	0.33	0.38	0.50	**35%**	357.51	330.46	228.35	**36%**	Z
15	Ludovic Alleaume	0.30	0.43	0.54	**44%**	208.60	229.98	140.43	**33%**	Z
16	Hubert Sauzeau 1	0.38	0.49	0.54	**29%**	286.27	274.22	253.60	**11%**	Z
17	Hubert Sauzeau 2	0.58	0.77	0.85	**32%**	359.85	216.34	162.85	**55%**	Z
18	Charles Müller	0.27	0.34	0.44	**39%**	423.32	407.67	158.34	**63%**	Z
19	Furcy de Lavault	0.32	0.42	0.66	**52%**	330.62	221.19	133.43	**60%**	Z
20	Louis Alexandre Cabié	0.62	0.72	0.96	**36%**	272.36	253.29	186.41	**32%**	Z
21	Louis Lessieux	0.37	0.46	0.61	**40%**	312.33	252.49	214.17	**31%**	Z
22	Jeannine Gilles-Murique	0.95	1.03	1.57	**39%**	142.19	122.07	104.93	**26%**	Z
23	*Night Watch* mockup canvas	0.41	0.72	0.74	**44%**	183.57	156.32	176.82	**4%**	Z
24	*pattina* lining canvas	0.37	0.42	0.51	**27%**	371.56	281.37	196.09	**47%**	Z
25	*patta* lining canvas	0.54	0.76	0.94	**43%**	238.53	153.66	101.13	**58%**	Z
26	canvassing '03f'	0.62	0.71	0.85	**28%**	191.06	163.57	125.27	**34%**	Z
WEFT		Weft yarn width				Weft TPM				twist
Specimen name		Small	Medium	Large	% Large-Small	Small	Medium	Large	% Small-Large	Z or S
1	plain canvas 1	0.38	0.41	0.55	**30%**	248.47	260.98	207.32	**17%**	Z
2	plain canvas 2	0.58	0.71	1.13	**49%**	205.37	161.43	119.35	**42%**	Z
3	plain canvas 3	0.36	0.59	0.98	**64%**	296.26	251.11	99.61	**66%**	Z
4	plain canvas 4	0.67	0.97	1.11	**40%**	172.27	134.03	117.80	**32%**	Z
5	plain canvas 5	0.47	0.59	0.77	**39%**	243.86	170.24	125.13	**49%**	Z
6	Domenico C. Malinconico	0.32	0.50	0.57	**44%**	393.67	145.00	134.67	**66%**	Z
7	Bernard d'Agesci	0.27	0.48	0.50	**47%**	293.05	289.28	163.69	**44%**	Z
8	medium paste lining canvas (IT)	0.53	0.79	0.97	**45%**	185.45	218.86	141.94	**23%**	Z
9	heavy paste lining canvas (IT)	0.47	0.80	0.81	**42%**	475.24	222.37	171.52	**64%**	Z
10	Fragonard medium paste lining	0.33	0.73	0.76	**57%**	268.46	131.10	166.60	**38%**	Z
11	Raffaele Postiglione	0.54	0.97	1.12	**52%**	201.35	150.00	85.68	**57%**	Z
12	Alfred Dehodencq	0.32	0.54	0.62	**49%**	403.85	174.84	150.46	**63%**	Z
13	Jules Gélibert	0.34	0.40	0.53	**36%**	234.11	297.55	192.11	**18%**	Z
14	Louis Augustin Auguin	0.31	0.32	0.46	**32%**	513.44	472.33	333.78	**35%**	Z
15	Ludovic Alleaume	0.28	0.34	0.40	**31%**	270.39	251.86	231.90	**14%**	Z
16	Hubert Sauzeau 1	0.37	0.41	0.40	**8%**	344.41	392.71	266.18	**23%**	Z
17	Hubert Sauzeau 2	0.50	0.46	0.63	**21%**	223.28	239.23	138.78	**38%**	Z
18	Charles Müller	0.19	0.31	0.40	**53%**	473.04	385.82	241.81	**49%**	Z
19	Furcy de Lavault	0.24	0.34	0.49	**51%**	541.13	354.36	175.30	**68%**	Z
20	Louis Alexandre Cabié	0.61	0.71	1.18	**48%**	191.07	198.97	94.84	**50%**	Z
21	Louis Lessieux	0.24	0.29	0.42	**43%**	444.86	353.41	224.57	**50%**	Z
22	Jeannine Gilles-Murique	1.11	1.06	1.64	**32%**	93.10	56.92	80.82	**13%**	Z
23	*Night Watch* mockup canvas	0.49	0.45	0.51	**3%**	249.46	261.26	229.32	**8%**	Z
24	*pattina* lining canvas	0.27	0.47	0.58	**53%**	358.79	174.71	177.12	**51%**	Z
25	*patta* lining canvas	0.60	0.76	0.87	**31%**	195.86	168.90	133.92	**32%**	Z
26	canvassing '03f'	0.61	0.66	0.79	**22%**	197.55	161.24	136.53	**31%**	Z

Note: TPM is higher for the thinner yarns.

the slightly higher yarn width in the warp (Table 4), may be related to its higher crimp (Table 7) and thread count (Table 3).

Discussion

Characteristics correlated to warp and weft

Within the set of 22 historical and 4 modern textiles, the analysis of the quantified morphological characteristics of the yarns shows recurring features correlated with the weave direction. The most relevant are listed in Table 8, and the presence of a higher crimp in the warp provides the strongest correlation (96%). A similarly high prevalence of warp crimp is also found in the literature, both in conservation (Flock 2020; Young and Jardine 2012) and textile engineering (Mertova, Neckar, and Muzaffar Ishtiaque 2016). Warp yarns are also wider (80%) and have a higher thread-count (77%), providing additional useful indicators. These seem to be directly related to the convenience of weaving practice, as it is easier and cheaper to produce a balanced textile with more warp yarns, which are wider to avoid them breaking during the weaving process. The weft yarns, on the other hand, are easy to reconnect, and this is actually done each

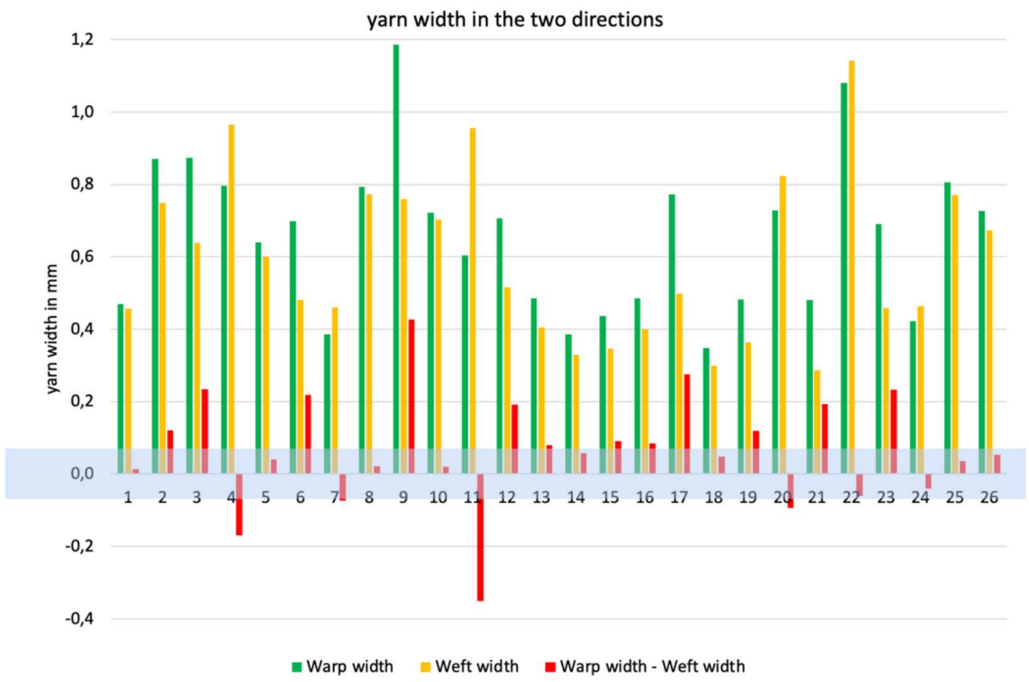

Figure 7. Measurements of the yarn's width weighted mean. The difference shows that the warp yarns are wider in 80% of the 26 canvases.

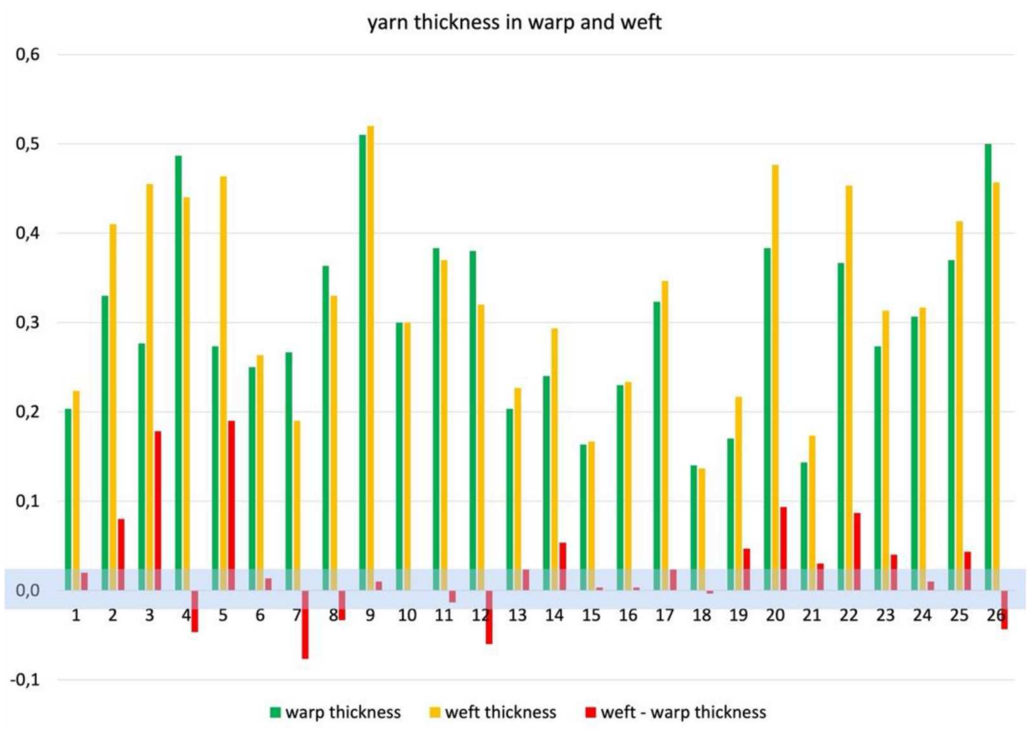

Figure 8. Weft yarns are thicker than the warp yarns in 67% of the cases, because they retain a more circular cross-section during weaving.

time the shuttle needs to be refilled. The consistency of the features revealed by this study allows direct correlations with manufacturing techniques, and apply to both hand-woven and industrial textiles. Experience gained during the research has shown that the difference in crimp is often clear enough to allow naked eye identification of the warp direction. All other features require instead a more detailed observation and measuring with the methods described.

The higher twist in the weft yarns follows the principle that thinner yarns have higher twist, with weft twist being higher in 65% of the cases. Additionally, weft retains a more circular shape, and the yarns are thicker in 67% of the cases. The z-axis compression is the other

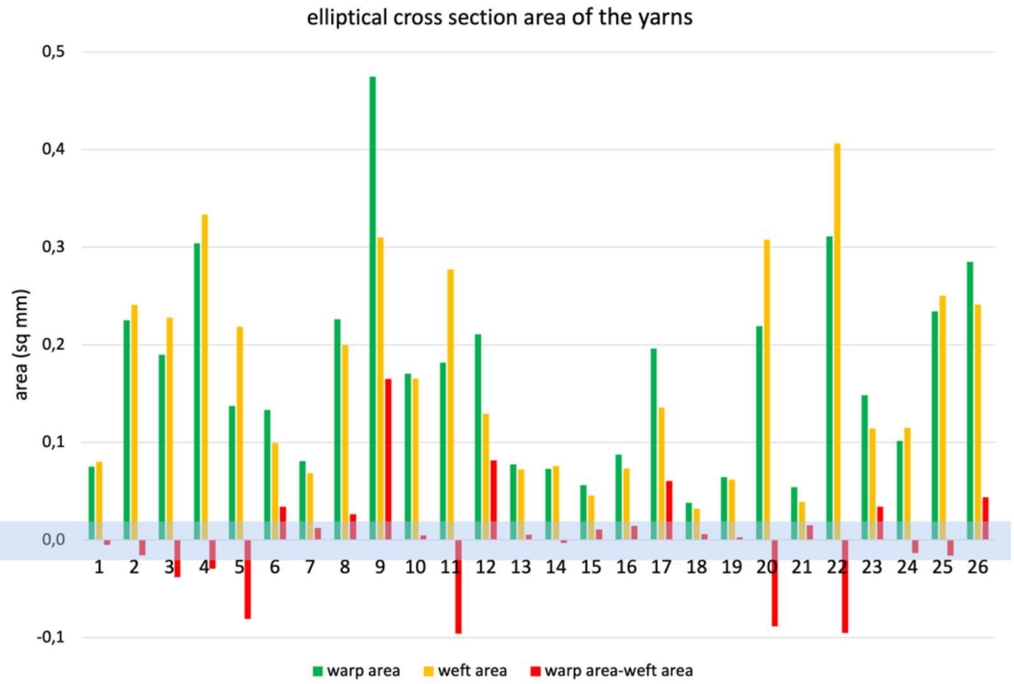

Figure 9. The area of the elliptical cross-section in warp and weft yarns, higher in the warp in only 54% of the cases.

Table 6. TPM and yarn width weighted means. In 17 cases, or 65%, weft has higher TPM.

		Yarn width w. means		TPM w. means		
Specimen name		Warp width	Weft width	Warp TPM	Weft TPM	Weft-warp
1	plain canvas 1	0.47	0.46	277.10	238.33	−38.77
2	plain canvas 2	0.87	0.75	140.48	161.66	21.18
3	plain canvas 3	0.87	0.64	150.43	229.62	79.20
4	plain canvas 4	0.80	0.97	193.05	134.86	−58.20
5	plain canvas 5	0.64	0.60	286.19	175.42	−110.77
6	Domenico C. Malinconico	0.70	0.48	186.54	197.85	11.31
7	Bernard d'Agesci	0.39	0.46	200.12	252.78	52.66
8	medium paste lining canvas (IT)	0.79	0.77	230.95	191.28	−39.67
9	heavy paste lining canvas (IT)	1.19	0.75	193.95	251.23	57.28
10	Fragonard medium paste lining	0.72	0.70	196.67	152.62	−44.05
11	Raffaele Postiglione	0.60	0.96	229.20	140.34	−88.86
12	Alfred Dehodencq	0.71	0.51	163.99	212.05	48.06
13	Jules Gélibert	0.49	0.41	244.21	288.50	44.29
14	Louis Augustin Auguin	0.39	0.33	324.45	464.63	140.17
15	Ludovic Alleaume	0.44	0.35	213.28	250.80	37.53
16	Hubert Sauzeau 1	0.48	0.40	272.11	366.49	94.38
17	Hubert Sauzeau 2	0.77	0.50	217.74	219.83	2.09
18	Charles Müller	0.35	0.30	362.42	380.99	18.57
19	Furcy de Lavault	0.48	0.36	204.36	339.70	135.34
20	Louis Alexandre Cabié	0.73	0.82	249.19	168.68	−80.51
21	Louis Lessieux	0.48	0.29	254.77	371.62	116.86
22	Jeannine Gilles-Murique	1.08	1.14	124.96	64.43	−60.52
23	*Night Watch* mockup canvas	0.69	0.46	162.12	253.06	90.94
24	*pattina* lining canvas	0.42	0.46	291.94	195.43	−96.51
25	*patta* lining canvas	0.81	0.77	143.27	160.30	17.03
26	canvassing '03f'	0.73	0.67	159.48	162.90	3.42

side of the same phenomenon, and the warp yarns take on a wider elliptical shape when bent over the weft, with a higher z-compression in 86% of the cases.

The recent introduction of automated measuring algorithms and artificial intelligence to the analysis of images of the textile supports of canvas painting has allowed obtaining quantitative measurements of the direction and frequency of the yarns, highlighting recurring patterns and irregularities (Johnson, Johnson, and Erdmann 2013; Nobel et al. 2018). Unfortunately, to the present date, yarn width and thickness, crimp, and twist can only be measured by visual inspection and it is not yet possible to map them on the textile using automated processes.

A largely non-destructive observation protocol was developed here, enabling the extraction of quantitative data from a limited sample size. The data collected and analysed in the present research is based on the observation of relatively small samples, due to the decision to observe samples from historical textiles and obtain unambiguous correlations with their tensile response. Having obtained useful data from

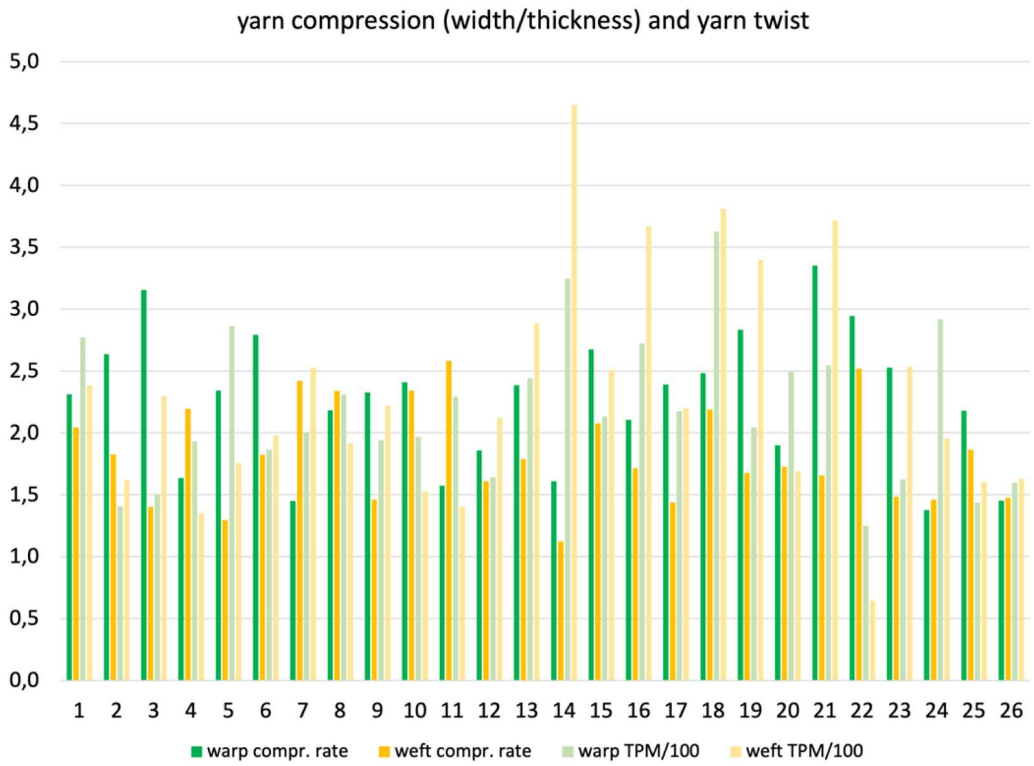

Figure 10. The yarn compression on the z axis of the textile (yarn width over thickness) and TPM. Higher TPM implies lower yarn compression.

Table 7. Crimp measures and their analysis.

		Crimp % measures						Means		Difference
Specimen name		Warp 1	Weft 1	Warp 2	Weft 2	Warp 3	Weft 3	Warp	Weft	Warp-weft
1	plain canvas 1	7.69	5.35	8.39	5.78	7.65	5.73	**7.91**	**5.62**	**2.29**
2	plain canvas 2	11.42	3.65	15.38	6.85	9.39	2.44	**12.06**	**4.31**	**7.75**
3	plain canvas 3	8.68	6.45	5.79	5.17	7.46	5.16	**7.31**	**5.59**	**1.72**
4	plain canvas 4	16.30	2.04	8.41	2.05	8.39	2.45	**11.03**	**2.18**	**8.85**
5	plain canvas 5	24.01	1.56	28.11	2.70	12.95	1.77	**21.69**	**2.01**	**19.68**
6	Domenico C. Malinconico	10.35	3.66	9.44	4.18	13.55	5.02	**11.11**	**4.29**	**6.83**
7	Bernard d'Agesci	4.73	10.22	6.82	3.99	7.56	7.65	**6.37**	**7.29**	**−0.92**
8	medium paste lining canvas (IT)	2.28	2.16	0.93	3.59	2.77	1.70	**1.99**	**2.48**	**−0.49**
9	heavy paste lining canvas (IT)	14.09	8.11	14.46	10.95	11.15	9.42	**13.23**	**9.49**	**3.74**
10	Fragonard medium paste lining	8.78	2.66	8.21	3.40	7.81	2.47	**8.27**	**2.84**	**5.42**
11	Raffaele Postiglione	8.09	2.49	2.93	4.25	4.45	3.06	**5.16**	**3.27**	**1.89**
12	Alfred Dehodencq	15.51	2.78	14.87	2.45	15.50	1.78	**15.29**	**2.34**	**12.96**
13	Jules Gélibert	12.30	3.40	11.36	3.58	12.10	3.71	**11.92**	**3.56**	**8.36**
14	Louis Augustin Auguin	17.67	5.80	13.78	3.87	7.44	4.28	**12.96**	**4.65**	**8.31**
15	Ludovic Alleaume	9.71	6.54	11.82	8.62	12.56	5.11	**11.36**	**6.76**	**4.61**
16	Hubert Sauzeau 1	13.28	6.38	9.54	5.63	18.14	5.18	**13.65**	**5.73**	**7.92**
17	Hubert Sauzeau 2	19.08	5.12	20.47	5.84	19.45	7.05	**19.67**	**6.00**	**13.66**
18	Charles Müller	11.82	4.96	8.49	6.47	10.48	5.66	**10.26**	**5.70**	**4.57**
19	Furcy de Lavault	13.68	3.00	14.28	3.63	14.66	2.45	**14.21**	**3.03**	**11.18**
20	Louis Alexandre Cabié	11.25	3.30	9.62	3.11	-	-	**10.44**	**3.21**	**7.23**
21	Louis Lessieux	11.90	5.09	13.27	7.38	15.94	6.44	**13.70**	**6.30**	**7.40**
22	Jeannine Gilles-Murique	7.72	3.92	5.07	3.81	-	-	**6.40**	**3.87**	**2.53**
23	*Night Watch* mockup canvas	7.03	1.04	7.63	2.63	6.83	1.06	**7.16**	**1.58**	**5.59**
24	*pattina* lining canvas	2.93	0.72	2.45	1.42	3.44	2.59	**2.94**	**1.58**	**1.36**
25	*patta* lining canvas	3.00	1.65	1.94	2.17	1.85	2.18	**2.26**	**2.00**	**0.26**
26	canvassing '03f'	5.69	2.59	5.86	2.59	4.91	2.34	**5.48**	**2.51**	**2.98**

small samples appears to be useful for the field of conservation and conservation science.

Warp and weft correlations in the literature

The following concise literature review outlines the most relevant approaches to the problem of warp and weft identification in historical textiles since the 1990s. It is not intended to be comprehensive but aims to highlight some of the key contributions to the identification of warp and weft, as well as the morphological description of the woven structures of canvas supports.

Rouba proposed experience-based methods to identify warp from weft by visually examining the

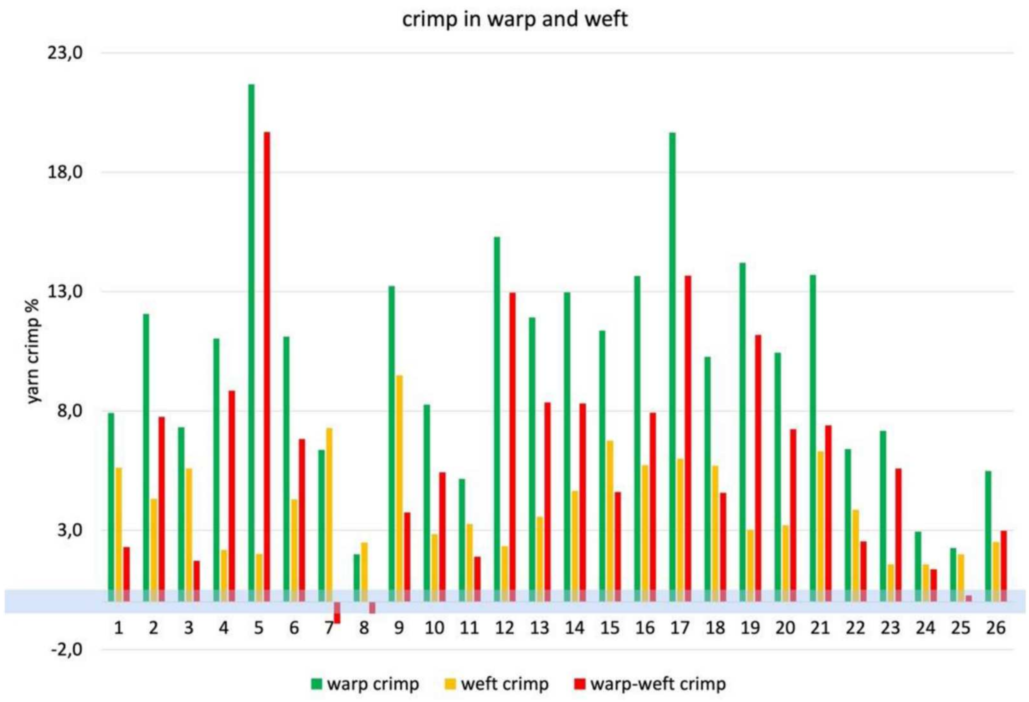

Figure 11. Crimp values in the warp are higher than in the weft in 96% of the cases.

reverse of the painting (Rouba 1992). Her descriptions define the warp yarns as being strictly parallel, while the weft yarns are sometimes curved and show discontinuities or marks made when the weft was cast on and beaten with the comb. She noted that the warp yarns are usually of better quality, woven regularly and with less defects, and may outnumber the weft yarns in thread count. Van de Wetering and Bosshard, on the other hand, investigated the canvas paintings supports structure through their X-ray images, to investigate the origin of the textiles and to distinguish warp from weft (van de Wetering 1997). The X-ray observation method enabled the definition of yarn orientation and density, local thickenings and deviations from straightness. They found that warp count is more consistent and often higher than the weft. The weft yarns were instead found to be of poorer quality, showing frequent thickenings. Additionally, they described recurring irregularities in the weft weave, such as stripes of uneven density caused by the beating of the comb or by the rolling of the fabric, and loose fibres accumulating on the warp causing the weft to bend over. Van de Wetering and Bosshard, along with Rouba, suggested that the warp yarns had more twist and less crimp. However, as they could not measure these characteristics directly, the authors presented these features as a hypothesis.

Table 8. General correlations with warp and weft in the 26 specimens.

Higher value	Crimp	z axis compress	Yarn width	Thread count	Yarn thickn.	Twist
Warp	96%	86%	80%	77%	33%	35%
Weft	4%	14%	20%	0%	67%	65%

Recent investigations using algorithms and artificial intelligence to describe the thread count and angle maps in warp and weft have made it possible to determine correlations between textile pieces belonging to different paintings (van der Maaten and Erdmann 2015). The X-ray observation method is similar to van der Wetering's studies, but the incomparably higher analytical capacity associated with the technology allows for a much deeper understanding.[25] As the research was extended to 400 van Gogh paintings (Johnson, Johnson, and Erdmann 2013), it also allowed for statistical studies. The overall correlations with warp and weft directions offered by these methods are similar to those deriving from van der Wetering's work. In Murashov, Berezin, and Ivanova (2019), similar results are obtained using raking light instead of X-ray or transmitted light observations. In the textile industry, automated methods to measure thread densities from simple images of the fabric are being developed (Aldemir, Özdemir, and Sarı 2019; Pan et al. 2015). Reliable correlations with warp and weft directions, and therefore their identification when a selvedge is not available, are also made available, based on the variability of the thread count and the thread angle within the textile.

The algorithms are used on the entire textile, and obtain a weaker correlation for the thread count in warp and weft.[26] Still, it must be noted that these methods provide an indirect description of the textile and not the physical measurement in a specific point. The differences found in the present study (Table 3 and Figure 6) see a mean prevalence of 2 warp yarns over the wefts in the 26 specimens, with a standard deviation of 1.8. Such absolute values are relatively small, and may become hidden in the general average values obtained with the automated algorithms. Although very useful for technical art history (and for industrial inspection), to the date, these methods cannot measure the twist and crimp of the yarns, nor their width or thickness.[27]

Conclusions and future work

Effective and relatively simple methods to measure usually inaccessible characteristics of historical textiles have been developed, organised and described in this paper. The protocols were tested on a heterogeneous group of samples, and the quantity of data allowed drawing a preliminary set of conclusions that will be challenged by the future steps of the research, on a wider set of specimens. It is interesting to note that strong correlations have been found for warp and weft yarns that promise a certain degree of reliability in their identification in the absence of a selvedge.

The future step is to test a larger number of historical textiles, that are currently being prepared. Statistical analysis will show the correlation between the observation of a specific characteristic of the yarns and the possibility to identify of the warp and weft in the absence of a selvedge, and how the probability is increased by the simultaneous observation of more than one characteristic. The other direction of the ongoing research is on the mechanical side, performing uniaxial and biaxial tensile tests on the observed specimens in order to build a correlation database with the characteristics studied here.

Glossary of terms

- **Fibres**. Long, thin, flexible strands of material that can be spun into yarn or thread, used in the production of textiles and fabrics.
- **Thread**. A yarn that is usually thin and highly twisted, adapted for sewing. Thread and yarn can be considered synonyms.
- **Yarn**. General definition of a long strand of twisted fibres used for weaving. Yarn and thread can be considered synonyms, but yarn was preferred here because it is a more general term. For the definition of the number of yarns per unit length of the textile, the term 'thread count' was chosen because it is of general use and changing it to 'yarn count' sounded unnatural.
- **Twist**. During the spinning process, the fibre strands are wound around their axis, thereby acquiring twist. High twist means high tensile strength and cohesion of the yarn.[28]
- **Warp**. The longitudinal yarns that are held in tension on a loom during the weaving process. They run parallel to the length of the fabric and serve as the foundation or backbone of the woven fabric, being lifted to form the shed in which the weft yarns are inserted.
- **Weft**. The transverse yarns that weave in and out of the warp yarns to make fabric during the shedding process.
- **Shedding**, **shed**. Process where the warp yarns are divided into sets to create an open space, or shed, through which the weft yarn is passed.
- **Crimp**. The waviness or bending of yarns within a fabric as they interlace with each other. It describes how much the yarns deviate from a straight line as they bend over and under other yarns. The crimp is usually expressed as the percentage of the extra length of the interlaced yarn in relation to the straight yarn.
- **Plain weave**. The pattern alternates every row, so the warp and weft interlace 1:1 at right angles, creating a uniform texture.
- **Basket weave**. The pattern is the same as in plain weave, but multiple warp and weft threads (usually two or more) are woven together as a unit, rather than individually.

Notes

1. The standard reference is the Tex, a direct measure of linear density, providing the weight in grams per 1 kilometre of yarn. Industrial yarns are weighed when rolled on bobbin, a simple operation with the additional advantage of lowering the error due to the length of the sample. When dealing with historical textiles, the length of the yarns available for weight measurement are often no more than a few centimetres and they are often contaminated with substances that affect their weight.
2. Original text in Italian available at: https://doi.org/10.5281/zenodo.13949451; English translation available at: https://doi.org/10.5281/zenodo.13949377
3. The author is currently carrying out tensile tests on the specimens examined in the present study, using the biaxial tester described in Iaccarino Idelson, Sánchez López, and Groves (2023).
4. The research presented in this paper is part of the PhD work by Antonio Iaccarino Idelson, with Roger Groves and Otto Bergsma as promotors (Iaccarino Idelson 2025).
5. The only exception is made for a 'basket weave' canvas, a 'plain weave' with two parallel yarns. The canvas was added to the group because it was deeply studied in a parallel project.
6. Among them the canvas used by A.E. Fragonard for his *François 1er armé chevalier par Bayard* to adapt its dimensions when it was first exhibited in the Louvre Museum in 1829
7. 'Canvassing the making. Understanding plain woven canvases of old master paintings by handweaving and analysing reconstructions', funded by the

Netherlands Institute for Conservation, Art and Science (NICAS) as a Small Project Grant. The project is directed by Prof. dr. R.G. Erdmann (University of Amsterdam/Rijksmuseum), with S.A.F. Smelt (Rijksmuseum); I. Meijssen (Ingeborg Meijssen Textiles); L. Hassink (Museum Bussemakerhuis); I. Verslype (Rijksmuseum). https://www.nicas-research.nl/projects/canvassing-the-making/
8. A correctly focused laser beam is very thin, thus causing only local heating. When dealing with cellulosic fibres, the affected part of the textile sublimes, the perimeter is carbonised, and no sealing effect is visible, as the residual ashes fall off spontaneously.
9. Images taken with a 2:1 macro lens. When cropped close to the sample perimeter, as in Figure 2, a square image measuring 21.7 mm contains 3230 pixels per side, at a resolution of 6.7 microns/pixel.
10. Rhinoceros, Robert McNeel & Associates version 7 was used, but the same tools are found in earlier versions and in other software such as Autocad, and in libreware and non-proprietary applications. The method is described in the next section.
11. The same result could be obtained inserting a scale bar in the image.
12. Environmental data: temperature 20°C (+/- 1), and relative humidity 50% (+/- 5).
13. Gibertini ETERNITY 100 SMI.
14. The total area of a cruciform sample, with the indentations in the weft arms, is 297.12 mm^2.
15. For specimens 6 and 9 only three samples were available.
16. Micrometre model SXQFC-001eu, Beslands. Though the very low value of approx. 0.02 N/cm^2 was used for the compression force, a certain crushing of the sample, not noticeable during the tests, must be taken into account.
17. The identification of the fibres was carried out at the Laboratory of Diagnostics and Materials Science 'Michele Cordaro', Department of Economics, Engineering, Society and Business Organizations (DEIM), University of Tuscia, by Dr. Giorgia Agresti and Prof. Ulderico Santamaria.
18. An early example is found in *British Standard Handbook n.11* (1963). Updated versions are ISO-3071-2020 and ISO 6588-1:2021.
19. In recent years it has become a standardised procedure at the abegg-Stiftung textile conservation studio (this was learned during a private communication).
20. Conservator Chris Stavroudis demonstrates how to use an agarose plug to measure the surface conductivity and pH of a painted surface with a drop of water and an agarose plug https://youtu.be/bOqZEE7Kb8Y?si=Yz1ICyDjNksQnVfF
21. See the TAAPI T529 standard (1999).
22. This is a professional statement by author Idelson, who has used the method to measure the pH of canvas paintings in conservation practice since 2013.
23. Measurements were taken on unstretched, laser-cut samples. It would be valuable to repeat the measurements on samples stretched under a known tension, as a reduction in value is expected.
24. Special tanks to Clemente Sironi, from the textile company Sironi in Italy, and to the hand-weaver Ingeborg Meijssen for the useful and interesting conversations on this subject.
25. https://countingvermeer.rkdstudies.nl/6-exploiting-weave-maps/
26. Don H. Johnson plotted the average thread counts for over 450 paintings (fifteenth to twentieth century) concluding that no telling warp/weft judgement can be made simply from average thread count. However, plotting the standard deviations revealed that the weft threads tend to have more variable thread counts. Personal communication.
27. It should be noted that methods based on the analysis of the entire image of a painting's textile support – whether from X-rays or raking light – face significant limitations when the painting has been lined.
28. The Centre International d'Etudes des Textiles Anciens has a useful online dictionary at: https://vocabulaire.cieta.fr/en/twist-n

Acknowledgements

Thanks to Giorgia Agresti and Ulderico Santamaria (University of Tuscia, Italy) for the fibre identifications; Daniela Di Benedetto (Equilibrarte srl, Italy) and Justine Sionneau (Atelier Buti, France) for support with pH measurement and thread count; and Patrick Buti (Atelier Buti, France) for providing most of the naturally aged samples. Thanks to the 'Canvassing the making' team, and in particular to Robert Erdmann (Rijksmuseum, Amsterdam), Susan Smelt (Rijksmuseum, Amsterdam), and Ingeborg Meijssen (professional weaver and historical textile researcher), for interesting discussion and for sharing information and one of their textiles. Thanks to Daniela Di Benedetto (Equilibrarte srl, Italy), Caroline Vogt (Abegg-Stiftung, Switzerland), Clemente Sironi (Tessitura Sironi, Italy), Roberta Genta (Torino university, Italy), and Manuela Zarbà (Istituto Centrale per il Restauro, Rome) for useful discussions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Antonio Iaccarino Idelson http://orcid.org/0000-0001-5875-6116
Otto Bergsma http://orcid.org/0009-0004-8245-0634
Roger Groves http://orcid.org/0000-0001-9169-9256

References

Aldemir, E., H. Özdemir, and Z. Sarı. 2019. "An Improved Gray Line Profile Method to Inspect the Warp–weft Density of Fabrics." *The Journal of The Textile Institute* 110 (1): 105–116. https://doi.org/10.1080/00405000.2018.1467743.

Behera, B. K., and P. K. Hari. 2010. *Woven Textile Structure: Theory and Applications*. Woodhead Publishing Series on Textiles, 115. Cambridge: Woodhead Publshing.

Berry, G. M., S. P. Hersh, P. A. Tucker, N. Kerr, and D. M. McElwain. 1978. "Properties of Some Archaeological Textiles. ICOM Committee for Conservation 5th Triennial Meeting Zagreb Yugoslavia 1-8 October 1978."

Böhme, N., M. Anders, T. Reichelt, K. Schuhmann, A. Bridarolli, and A. Chevalier. 2020. "New Treatments for Canvas

Consolidation and Conservation." *Heritage Science* 8 (1): 16. https://doi.org/10.1186/s40494-020-0362-y.

British Standards Handbook, n. 11. 1963. *Methods of Test for Textiles*. London: British Standards Institution.

Conti, W., and E. Tassinari. 1973. "Un metodo ottico per la determinazione della torsione dei filati", in: Urbani, G. "Problemi di Conservazione" Editore Compositori, Bologna, p. 131. Original text in Italian. English translation available at https://doi.org/10.5281/zenodo.13949377

Flock, H. 2020. *Einzelfadenverklebung in der Gemälderestaurierung: Klebstoffe, Prüfsystematik und Ergebnisse*. Saarbrücken: Saarbrücken University.

Iaccarino Idelson, A. 2025. "Tension on a Stretcher: Mechanical and Morphological Characteristics of Canvas Paintings Supports." PhD Thesis, Technical University of Delft, The Netherlands.

Iaccarino Idelson, A., O. Bergsma, and R. M. Groves. 2025. "Methodology for Measures of Twist and Crimp in Historical Textiles and Canvas Paintings Supports." *Journal of Cultural Heritage* 71:1–9. https://doi.org/10.1016/j.culher.2024.10.016.

Iaccarino Idelson, A., M. Sánchez López, and R. M. Groves. 2023. "An Open-source Biaxial Tensile Tester with Automated Pre-tensioning for Mechanical Studies of Canvas Paintings." *HardwareX* 14: 1–21. https://doi.org/10.1016/j.ohx.2023.e00412.

Johnson, D. H., C. R. Johnson, and R. G. Erdmann. 2013. "Weave Analysis of Paintings on Canvas from Radiographs." *Signal Processing* 93 (3): 527–540. https://doi.org/10.1016/j.sigpro.2012.05.029.

Kania, K. 2013. "The Spinning Experiment: Influences on Yarn in Spinning with a Hand-spindle." In *Ancient Textiles, Modern Science: Re-creating Techniques Through Experiments*. Proceedings of the First and Second European Textile Forum 2009 and 2010, edited by H. Hopkins, 11–28. Oxford: Oxbow.

Kolcavova Sirkova, B., and M. Vysanska. 2012. "Methodology of Evaluation of Fabric Geometry on the Basis of Fabric Cross-section." *Fibres & Textiles in Eastern Europe* 20:41–47.

Kovar, R. 2011. "Length of the Yarn in Plain-weave Crimp Wave." *The Journal of The Textile Institute* 102 (7): 582–597. https://doi.org/10.1080/00405000.2010.498175.

Markova, I. 2019. *Textile Fibre Microscopy - A Practical Approach*. Hoboken, NJ: Wiley.

Mertova, I., B. Neckar, and S. Muzaffar Ishtiaque. 2016. "New Method to Measure Yarn Crimp in Woven Fabric." *Textile Research Journal* 86 (10): 1084–1096. https://doi.org/10.1177/0040517514551464

Murashov, D. M., A. V. Berezin, and E. Y. Ivanova. 2019. "Measuring Parameters of Canvas Texture from Images of Paintings Obtained in Raking Light." *Journal of Physics: Conference Series* 1368 (3): 032024. https://doi.org/10.1088/1742-6596/1368/3/032024.

Neckář, B., and D. Das. 2018. *Theory of Structure and Mechanics of Yarns*. *Woodhead Publishing India in Textiles Series*. New Delhi: Woodhead Publishing India PVT Limited.

Neckář, B., and D. Das. 2019. "Computational Methodology for Determination of Yarn Twist and Diameter." *The Journal of The Textile Institute* 110 (11): 1660–1671. https://doi.org/10.1080/00405000.2019.1611524.

Nobel, P., E. van Duijn, E. Hermens, K. Keune, A. van Loon, S. Smelt, G. Tauber, and R. Erdmann. 2018. "An Exceptional Commission." *The Rijksmuseum Bulletin* 66 (4): 308–345. https://doi.org/10.52476/trb.9762.

Ostergard, E. 2004. *Woven into the Earth: Textiles from Norse Greenland*. Aarhus: Aarhus University Press.

Pan, R., W. Gao, Z. Li, J. Gou, J. Zhang, and D. Zhu. 2015. "Measuring Thread Densities of Woven Fabric Using the Fourier Transform." *Fibres & Textiles in Eastern Europe* 1 (109): 35–40.

Peirce, F. T. 1937. "The Geometry of Cloth Structure." *Journal of the Textile Institute Transactions* 5 (3): T45–T96. https://doi.org/10.1080/19447023708658809.

Rota, E., C. Bozzi, P. Cremonesi, and A. Lucchini. 2021. "Study of the Best Methodology for Measuring Surface pH of Linen Canvas." *Studies in Conservation* 66 (6): 313–320. https://doi.org/10.1080/00393630.2020.1838711.

Rouba, B. J. 1992. "Die Leinwandstrukturanalyse und ihre Anwendung für die Gemäldekonservierung". *Restauratorenblätter Malerei und Textil* 13: 79–89.

Saville, B. P. and Textile Institute (Manchester, England). 1999. *Physical Testing of Textiles*. Cambridge: Woodhead Publishing, Ltd. In association with the Textile Institute.

Seiler-Baldinger, A. 1996. *Textiles: A Classification of Techniques*. Washington, DC: Smithsonian Institution Press.

van de Wetering, E. 1997. *Rembrandt: The Painter at Work*. Amsterdam: Amsterdam University Press.

van der Maaten, L., and R. Erdmann. 2015, July. "Automatic Thread-Level Canvas Analysis. A Machine-Learning Approach to Analyzing the Canvas of Paintings." *Signal Processing Magazine* 32 (4): 38–45. https://doi.org/10.1109/MSP.2015.2407091

Young, C. R. T., and R. D. Hibberd. 1999. "Biaxial Tensile Testing of Paintings on Canvas." *Studies in Conservation* 44 (2): 129–141. https://doi.org/10.1179/sic.1999.44.2.129.

Young, C., and S. Jardine. 2012. "Fabrics for the Twenty-First Century: As Artist Canvas and for the Structural Reinforcement of Easel Paintings on Canvas." *Studies in Conservation* 57 (4): 237–225. https://doi.org/10.1179/2047058412Y.0000000007.