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Original article

Methodology for measures of twist and crimp in canvas paintings supports and historical textiles [☆]

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ABSTRACT

Twist and crimp values are of paramount importance to the textile industry in understanding the properties and performance of a textile, and their quantification has been a subject of study since the early 20th century. Twist and crimp are the result of how the fibers have been modified from the original bundle to shape the textile, so the industrial methods used to measure them are based on mechanically reversing such deformations. The same information is needed to study the mechanics of historical fabrics such as canvas paintings supports and historical textiles, but they are more difficult to obtain because these are often brittle and impregnated with foreign materials, less homogeneous and very limited in availability for sampling. Therefore, such fundamental parameters are usually unavailable for conservation studies.

This paper examines the protocols used in the textile industry and proposes new methods, developed from previous research, for the reliable measurement of twist and crimp in historical textiles. The twist measurement method is non-destructive as it is based on observing the textile and the fibers on the surface of the yarn. Crimp is the undulation of the interlaced yarns and its measurement is an invasive examination of the internal structure of the textile, as it requires the observation of individual yarns. Both methods, applied here to a group of historical textiles, provide data in accordance with the current parameters of the textile industry, and their use is relatively simple and inexpensive.

Introduction and general definitions

Twist and crimp values are of paramount importance to the textile industry in understanding the properties and performance of a textile, and their quantification has been a subject of study since the early 20th century [Pierce, 1937]. The capability to quantify them for historical textiles would allow a much deeper understanding of the textiles' mechanical properties and behavior, thus improving the possibilities for their conservation and guide treatment choices. Quantitative data describing historical textiles would allow morphological comparisons and the use of statistics, and would improve the robustness of conservation strategies and predictive digital simulations. The amount of twist in a yarn contributes to its cohesion and tensile response, and the amount of crimp has an effect on the stress-strain curve of a textile, because a high crimp value in the yarns implies the presence of a long decrimping phase in the initial part of its response to a tensile load. To give practical examples, a textile to be used for lining should have a relatively high tensile modulus, and this is more likely to be found in a textile with low crimp and high twist values. On the other hand, the canvas support of a painting will be more prone to creep under tension if the yarns have high crimp and low twist values.

Twist

Twisting the fibers precedes weaving, being the process by which they are arranged around the axis of the yarn [1]. Twist is introduced by spinning the fibers in a number of turns that depends on the amount of fibers and on their properties, to meet the expected requirements of the yarn. Twist provides the first level of organization of the fibers and determines the appearance, bending stiffness, and tensile strength of the yarn, as well as uniformity, stretch and stiffness of the textile, its durability and even color depth [2]. With natural fibers, strength is imparted by increasing the friction between them, and as the twist increases, the lateral force that packs the fibers together also increases, allowing more fibers to contribute to the cohesion and tensile resistance of the yarn. However, as the twist exceeds the ideal optimum level [3] the angle that the fibers form with the yarn axis increases, and they contribute less to yarn strength because they are not aligned with the tensile force. Natural fibers are highly variable in length,

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[☆] Link to a video abstract DOI:https://zenodo.org/records/14003644

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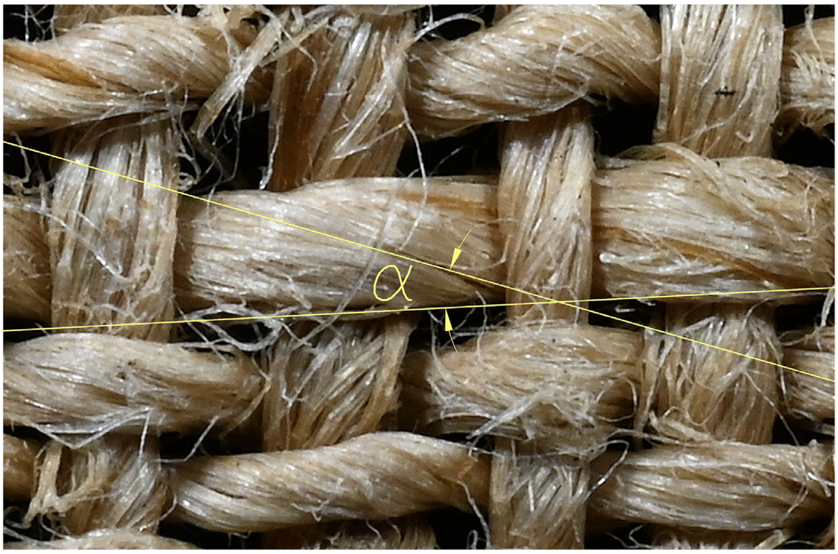

Fig. 1. Twist angle traced on the fibers of a yarn.

thickness, and flexural stiffness. As a result, differences in twist along the yarn are very common, especially in traditional spinning processes, and so are differences in the thickness of the resulting yarns [4]. Fibers can be twisted clockwise or counterclockwise, and the resulting yarn twist is defined as Z or S, as the direction of the fibers visible on the side of the yarn aligns with the transverse element of the letter. It is most common to see single ply yarns with a Z twist, while S twist is more common in multi-ply yarns. The standard reference for measuring twist is the number of turns per unit length, Twist Per Meter (TPM) [5], and twist is typically measured by unwinding a yarn and counting how many turns it takes for the fibers to become parallel to the yarn axis [3]. Twist meters or twist testers are machines that mechanically unwind the yarn while counting the revolutions of the axis on which the yarn is clamped. Determining when the fibers are straight again and have not yet begun to twist in the opposite direction is not easy for an automated process that does not involve complex optical observations. For this reason, force and elongation sensors can be incorporated to reduce error. The procedure is described in [6], which requires yarn samples of considerable length, at least 20 cm. To reduce error, and to account for the natural variability of twist related to the local thickness and stiffness of the fiber bundle, often twist tester allow for longer samples, up to 50 or 100 cm. We will see that this also applies to crimp measurements.

The impossibility of unwinding the fibers of a degraded or impregnated historical yarn, and the variability of its twist, have been enough to discourage any attempt to measure twist for conservation purposes. The only information available are the twist direction (Z or S) and the “twist angle” as defined in the Pierce model [7,8]. The twist angle is described by the tangent to the side of the yarn and the direction of a twisted fiber (α in Fig. 1). It provides a semi-quantitative description of the twist at a given point in the yarn, that can only be used for comparation purposes. A study published in 1973 [9] by two textile engineers studying old canvas paintings [10] proposed an optical method to calculate the number of TPM[1] based on the same geometry used to observe the twist angle (as we will see in Fig. 4). A similar procedure is found in [11], where it is used as a starting point for a digital image processing method to calculate TPM in textile engineering. An analog computational approach can also be found in [3].

Crimp

Crimp is the waviness imparted to the warp and weft yarns of a fabric by their interlacing. The degree of crimp is among the most important parameters in textile engineering and has a huge impact on the properties of a woven structure. It has therefore been the subject of studies that are fundamental references in the field since the mid 19th century [7]. Important commodity characteristics of a fabric are related to crimp, such as its drape and "hand”, its flexibility and thermal properties, and even the ballistic performance of special textiles [12]. Considering an unrestrained canvas, a higher crimp means greater shrinkage upon wetting [7,13]. The amount of crimp also describes the length of yarn needed to weave a textile, as a crimped yarn has a longer path than the sheer amplitude of the fabric.[2] When considering tensile properties, tension reduces the waviness of the yarns, thus de-crimping them as they are stretched. Under uniaxial loading, the effect is to transfer crimp from the yarns in one direction to those in the opposite direction, while under biaxial loading the yarns under tension mutually influence the de-crimping in the opposite direction. The standard reference [14] is the crimp % value, measured on a yarn taken out from a textile without changing its shape [5]. The yarn is measured and then stretched to remove its crimp and measure its uncrimped length, or the length it had before weaving. However, pulling on a yarn will eventually cause it to overstretch if the force exceeds that needed to straighten it, and the international standards [15], is an often-used example, aim at avoiding the problem.[3] Such measurements involve a considerable degree of approximation, which is compensated for by the length of the sample, again in the range of 50 or 100 cm. Most commercially available crimp testers mark

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[1] The English version of the paper can be downloaded here: https://doi.org/10.5281/zenodo.13949377.

[2] When talking about twist, a textile manufacturer will typically refer to the amount yarn length beyond that required for the final textile product, rather than to the shape the yarns take during weaving. This implies specific “craftsman nomenclature”: in the warp “shortening” or “shrinkage” are used, in Italian “raccorciamento”; in the weft direction, the technical term “take-up”, in Italian “rimborso”, that refers to the shrinkage but also to the methods and mechanical procedures used to control the tension in the weft.

[3] The existence of different standards in use demonstrates the sensitive nature of the problem.

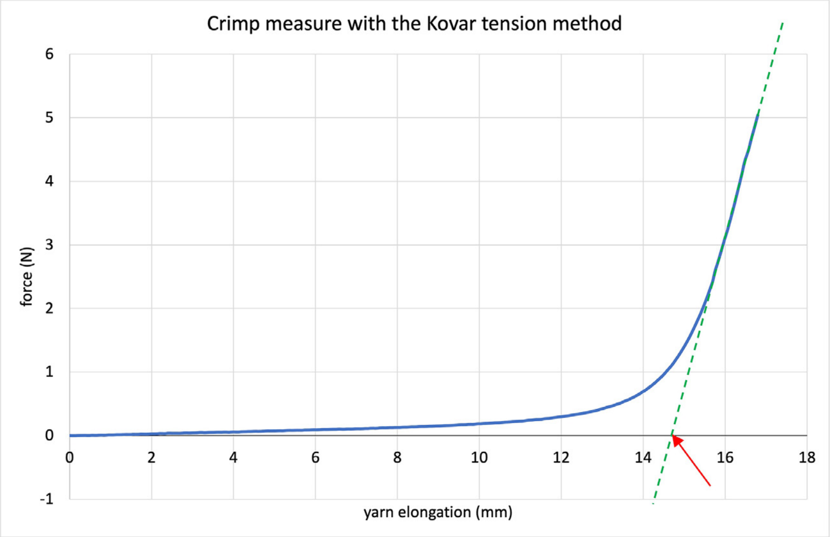

Fig. 2. Observation of the yarn tensile plot according to Kovar. The point of intersection on the abscissa marked with the red arrow is the value of the yarn's decrimping elongation.

the operation as complete when a force limit is reached, or when the yarn appearance is considered straight enough.

Mechanical methods are confronted with the problem that the yarn retains residual deformations when pulled straight, what implies a natural tendency to pulling too far. However, after a certain level of tension, elongation is due to the yarn elastic response, if not to fiber slippage. It is therefore difficult to decide when to end the test. For this reason, the introduction of the analysis of the stress-strain curve of the yarn obtained with a tensile tester was proposed [16]. A further improvement [17] is based on the observation of the tensile plot of the yarn,[4] as in Fig. 2. The first part of the plot is relatively straight and almost parallel to the abscissa axis, as it describes the low force needed in the decrimping phase, when the fibers recover their original straight configuration. As the yarn begins to respond to tension, a deflection point appears in the load curve and, to obtain a repeatable observation, the reading is given by the extension of the straight part of the curve, corresponding to the elastic behavior of the yarn under tension, at the point of intersection with the x-axis. The plot in Fig. 2 was obtained repeating Kovar's procedure with a tensile tester [18], and this allowed learning that the results can vary with the initial tension of the yarn. This is because insufficient initial tension will produce a longer stretch, indistinguishable from the expected decrimping phase since the force value is also close to zero. Too high initial tension will instead partially remove the crimp from the yarn before the test is started and also produce a false information. An alternative approach is based on the observation of a cross section of the textile under a microscope, which is sometimes preferred because microscopes are common in scientific laboratories. Research on the measurement of crimp through the image of a cross section was conducted at the Technical University of Liberec in the Czech Republic [19], where a line was drawn along the neutral axis of the crimped yarn in the cross section of the textile using dedicated software. The length of the neutral axis was measured using the same software and represents the length the yarn would have in a fully uncrimped form, not involving any mechanical deformation. The method was compared with the mechanical approach in [20] and with different geometrical approximations in [21] on industrial textiles, arriving at the general conclusion that its accuracy is equal or higher.

References to crimp measurements in conservation are very rare. In [22] we see the use of a geometric model derived from the Pierce model [7] to calculate crimp in modern textiles for use in lining treatments. The method uses the microscope image of a yarn extracted from the textile (length not specified) to measure the wavelength λ and amplitude A of its crimp wave to calculate a crimp factor through a dedicated equation. The choice of using a photographic image of the yarn instead of a resin-embedded cross section is very convenient, and helps reducing time and costs required for the observation. However, the equation has been tested for the historical specimens in this paper and found to produce inconsistent results for irregular, hand-woven textiles. The reason seems to reside in the fact that the equation describes a waveform consisting of a series of semicircles, as in Pierce, which does not correspond to historical textiles. Calculations of crimp based on several geometrical approximations, including those derived from Pierce, have been discussed and analyzed in [Kolcavová Sirková & Mertová 2020] and appear to be of frequent use for industrial fabrics, in which the waveform of the crimped yarn is homogeneous and more predictable. Methods that use the actual waveform of the crimped yarn to extract its uncrimped length, such as in [19], are therefore more compatible with the irregular crimp forms in historical textiles. It should also be noted that the information so obtained represents the average crimp in the entire sample image. With these arguments in mind, a simplified and adapted version of such a method for calculating the crimp % value has been developed in this paper and will be described in detail.

Research aim

The purpose of this paper is to contribute to the study of the degree of twist and crimp in the yarns that constitute historical fabrics. Twist and crimp are the result of the way the fibers have been tweaked and organized to form the textile; therefore, as we have seen, the standard measurement methods are based on mechanically reversing these deformations until they return to their initial unorganized state [5,14,23]. When testing naturally aged canvases, the availability of samples of suitable dimensions is a major limiting factor. In addition, naturally aged yarns are fragile and would break before the mechanical process required for the

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[4] Sample yarns 200 mm long, with a gauge length of 195 mm (as 25mm at each end are used for clamping), tested at the speed of 120 mm/min.

Table 1
General description of the specimens.

Plain weave linen canvases				Tread count		Twist S/Z		Weight and thickness	
Sample name	Weaving	Fibers	Date	Warp	Weft	Warp	Weft	g/m^2	mm
D. Malinconico	handmade	hemp	1728	13	13	Z	Z	244	0.26
B. d'Agesci	handmade	hemp	1817	18.7	17	Z	Z	334	0.41
R. Postiglione	handmade	linen	1845	8	8	Z	Z	265	0.66
J. Gélibert	machine	linen	1881	24	18.7	Z	Z	238	0.45
18th c. lining canvas	handmade	hemp	late 18th c.	7	7	Z	Z	166	0.48
L. A. Auguin	machine	linen	1885	25.3	25	Z	Z	296	0.22
L. Alleaume	machine	linen	1887	24	21.7	Z	Z	248	0.44
C. Müller	machine	linen	late 19th c.	31.3	29	Z	Z	150	0.26
A. E. Fragonard	machine	hemp	mid 19th c.	13.7	11.3	Z	Z	397	0.68
Basket weave lining canvas	machine	linen	1975	20.0	16.0	Z	Z	380	0.72
Pattina lining canvas	machine	linen	2015	9	9	Z	Z	149	0.44

measurement is complete [10]. Furthermore, in a painted canvas, the yarns are locked into three-dimensional structures, and unwinding or decrimping them is simply not an option. Data on these two key parameters are therefore typically unavailable for the characterization of historical textiles and for the canvases that support paintings. The aim was therefore to develop methods to measure these two fundamental characteristics on complex historical textiles, knowing that methods were not currently available, although they appeared to be highly needed.

Materials and methods proposed for twist and crimp measurements

Specimens

This study focuses on a group of naturally aged historical specimens from paintings with a known provenance (author and date provided), and two modern canvases have been included, to provide the large and uncontaminated yarn samples needed to validate the twist and crimp measures with standard mechanical procedures. In order to simplify data analysis, all textiles are in plain weave, with the only exception being the "basket weave" canvas, added to the group because it was deeply studied for the making of a mockup of The Night Watch.[5] A basket weave is not substantially different, as the yarns run in twin couples following a plain weave pattern. All specimens in the group have a selvedge, thus locating warp and weft. None has preparation or paint layers. The microscope identification of the natural fibers was carried out at the Università della Tuscia, Viterbo (Italy)[6]. The detailed list of the specimens is in Table 1.

Sample preparation and observation procedure

Historical textiles require a specific approach to sample selection and preparation. When small samples are available, they are often also difficult to manipulate, so the approach to naturally aged textiles must be as non-destructive as possible. The methods proposed here are based on the observation of a high-resolution[7] scaled image of the samples, rather than of a cross section as in [19]. The image is captured with a 2:1 macro lens, including a known length reference on the same plane as the sample. The image is then scaled to actual dimensions and precision measurements are made using computer-aided drawing (CAD) software,[8] as described below. The samples (from both historical and modern textiles) were laser cut according to a common shape [18] to obtain uniform dimensions for the observation area. Furthermore, since the samples are intended for mechanical testing, a clear correlation between the observed characteristics and their tensile response is established. While the twist measurements proposed here are completely non-destructive, crimp measurements still require the extraction of yarns from the textile in the warp and weft directions. The crimp observation length is of at least 8 mm, with a typical length of 10–15 mm. The goal of this study is to make the process faster and easier, requiring less specialized equipment, more affordable, and more widely available.

The intrinsic variability of handmade or naturally aged textiles requires a different approach than the study of industrial products. The inhomogeneity of the fiber bundles used for spinning, with fibers locally thicker or locally stiffer, result in yarn diameters varying widely. It was decided to divide the yarns within the observation area into three size-based sets, from thinnest to widest; the most representative of each set was selected and measured in three locations. The result is thus a matrix divided into three subsets, each represented by three measurements, for a total of 9 measurements in weft and 9 in warp (see Fig. 3). The method makes it possible to obtain a weighted mean that takes into account the numerosity of each class, thus providing an information that can be considered reliable and meaningful for the observation area for the measures of twist.

Theory and calculation

Description of the method for twist measurements in historical textiles

The method is an updated version of the previously mentioned Conti-Tassinari work [10], that used a goniometric eyepiece to construct a simple geometry on the image of the canvas. The geometry is illustrated in Fig. 4: the tangent, parallel to one side of the yarn, is drawn (1) and then offset to the opposite side (2), including its width; a diagonal line is traced along the curvature of the twisted fibers visible on the surface (3); the adjacent perpendicular segment provides the local measure of the yarn width (4), and forms a right-angle triangle with the second cathetus named "L". The length of L (in mm) is the value of L in the simple equation used to calculate the Twists Per Meter at a specific location of the yarn: TPM=318/L. Conti and Tassinari validated their method by comparing the results it produced for modern canvases, with the

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[5] The project is still ongoing and will soon be published.

[6] Università della Tuscia, Viterbo, Group of Diagnostics and Materials Science, with the participation and under the supervision of by Dr. Giorgia Agresti and Prof. Ulderico Santamaria.

[7] When cropped close to the sample perimeter, a square image measuring 21.7mm contains 3230 pixels per side, at a resolution of 6.7 micron/pixel.

[8] 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.

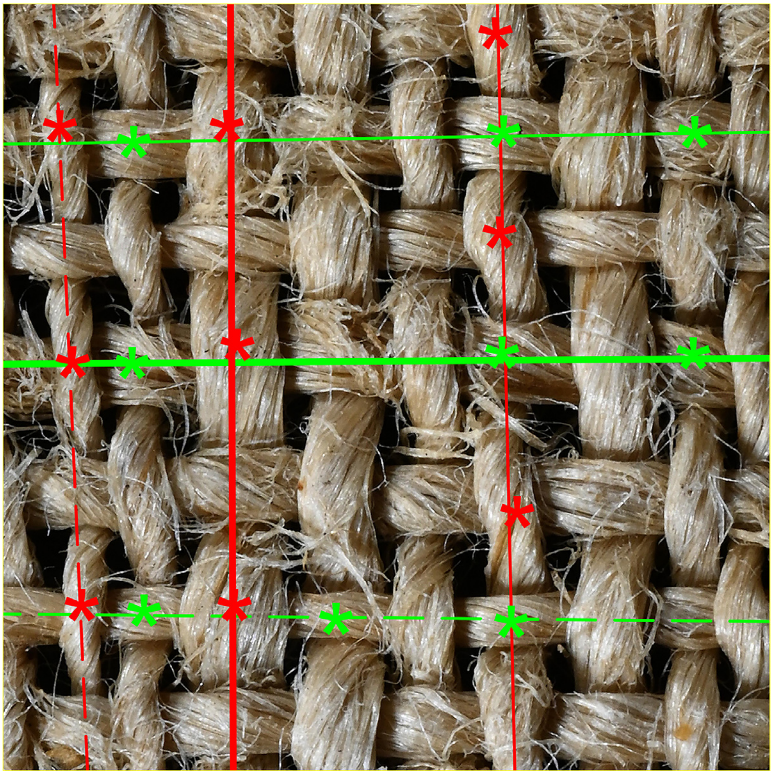

Fig. 3. Yarns in warp (red) and weft (green) selected as representative of the Small (S), Medium (M) and Large (L) width subsets within the 1cm^2 observation area, and the observation points.

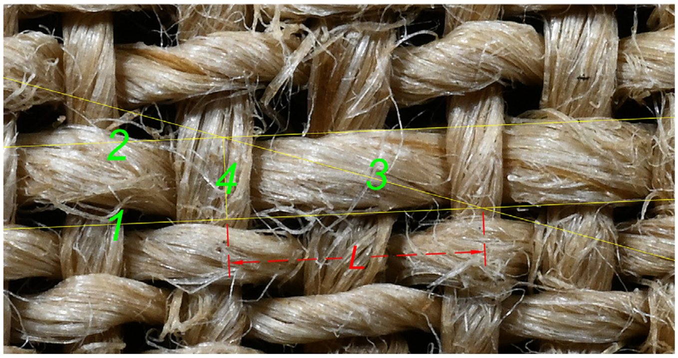

Fig. 4. The geometry used for the TPM calculation in the Conti and Tassinari method.

values obtained by unwinding the same yarns object of observations, using a twist meter.[9] Their conclusion was that if the observation is made in the straight strands between two crossing points in the woven structure, the expected error is lower than at the crossings where the superimposed yarns have a curved, elliptical section. They reported a level of error between 5 % and 15 %, depending on the curvature of the section of the yarn observed.[10]

The method proposed here differs from that of Conti and Tassinari in the use of a digital camera, and of a CAD software to scale and take measurements on the image file, instead of the goniometric eyepiece they recommended.

Description of the method for crimp measurements in historical textiles

The method deals with the irregular textiles encountered in the field of conservation, and it does not require the use of microscopes or proprietary software,[11] what seemed to be useful and necessary.

When measuring yarn crimp in a historical sample, it is critical to obtain data representing the longest portion of the waveform available in the image, considering the unpredictability of the yarn's path. The uneven diameters of the yarns generate different curves at each crossing and, on the other hand, the curve of the crimped yarn may have flattened peaks at yarn crossings due to surface crushing in naturally aged fabrics. Measuring the length of the neutral axis of the yarn by drawing a polyline on its axis solves such problems, because its length corresponds to that of the actual shape of the entire waveform. Therefore, its unevenness becomes irrelevant and, in fact, the measurement tolerates all kinds of irregularities. As explained, the method proposed here is based on using the image of the yarn to reveal its crimped shape. A section of the yarn is gently extracted from the side of the textile,[12] and is placed on double sided adhesive tape to stabilize its position while taking the macro photograph including a dimensional reference. As for the twist measures, the image is scaled to the real size in CAD. The "polyline" tool was found to be easy and flexible to use, and allows the actual shape of the yarn to be faithfully

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[9] The length of the test yarn was not specified.

[10] For a complete description and demonstration of the method, please refer to the English translation of the paper, available at https://doi.org/10.5281/zenodo.13949377.

[11] The use of dedicated software to draw the neutral axis of the yarn can introduce errors during the automated interpretation of the image, as reported in [20]. Automation of the procedure reduces unpredictable human error and time consumption, but it may be suitable for a significant workload in the textile industry rather than in conservation studies.

[12] Manual extraction of a crimped yarn sample is the common method in the textile industry. In this case, the yarns extracted measure between 10 and 20 mm, and not several decimeters.

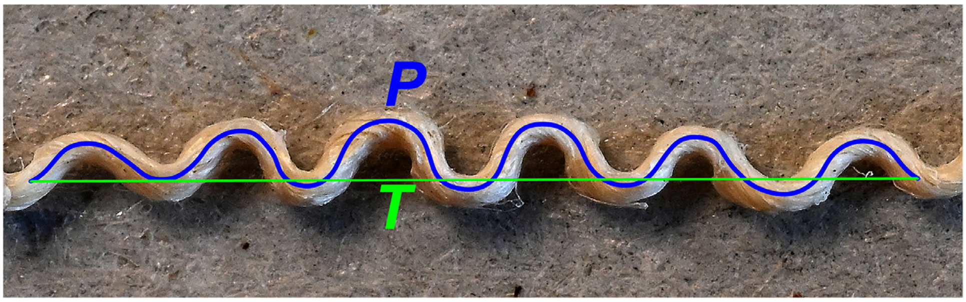

Fig. 5. The length of the uncrimped yarn **P** and of the textile **T** at the same location to calculate % crimp.

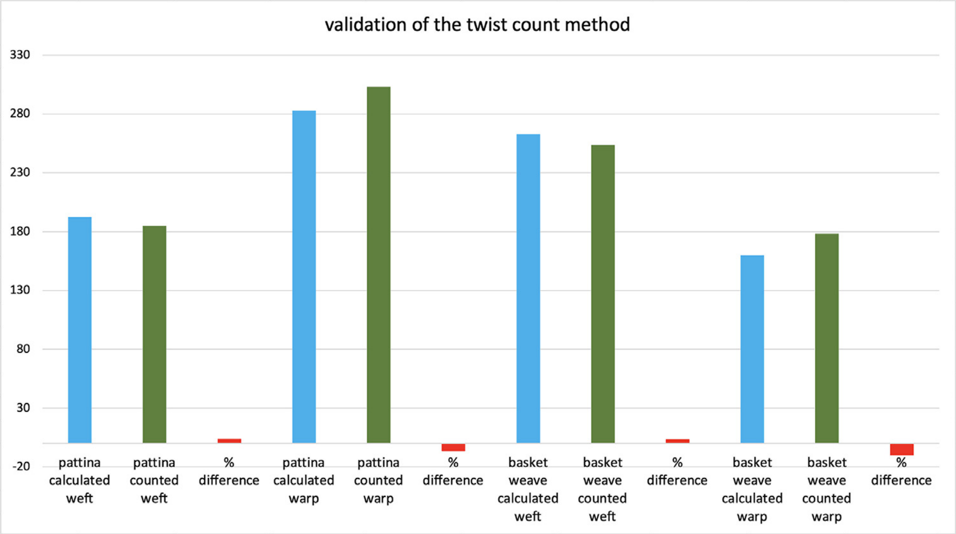

Fig. 6. Comparison between the TPM obtained through calculation and unwinding, and their difference.

copied. The length of the polyline, P, providing the full length of the yarn, is used to find the crimp % of the yarn by comparing it to the length T of the portion of textile, between the start and end points of the same polyline (as in Fig. 5), using the standard equation [7]. The procedure is easy, reliable, and less time consuming than the previously described alternatives.

$$Crimp\% = \frac{P - T}{P} \times 100 \quad (1)$$

Experimental results

Measures of Twist Per Meter

Before applying the Conti-Tassinari method, a new validation test was carried out for the present research, using the updated procedures on the two modern canvases. The mean of the values obtained with the optical method on three locations of a single yarn was compared with the twist count on the same yarns after manually unwinding them.[13] The results in (Fig 6) confirm the error predictions in the 1973 paper, as the error is between 3.5 % and 10.1 %.

Twist measurements are based on the observation of the small section exposed at each yarn crossing (as seen in Fig. 4) and therefore require a statistical treatment to become representative of the entire observation area,[14] as previously described (Fig. 3). The yarns are grouped into three classes according to their dimensions within the image of the sample, because yarn width is the main variable. Each yarn selected as representative of each class is measured for TPM (and yarn width) at three different locations, providing a mean value for each dimensional set. Using the number of units in each set, the weighted mean is calculated, providing a meaningful TPM number in warp and weft for each sample image, as seen in Table 2, where the highest subset values are highlighted in blue.

Measures of crimp %

A validation test was also carried out for the crimp measurements, comparing the results with those obtained using the tensile tester to reproduce the operation of a crimp tester on yarns from the “pattina” lining canvas. Yarns were put under tension[15] and the elongation value was used to calculate the crimp, as shown in Fig. 7. The values obtained with the polyline method for this textile are 2.94 % in the warp and 1.58 % in the weft (see Table 3), and the Kovar method (shown in Fig. 2) gives values of 3.3 % and 2.1 %. Another way of extracting a crimp value from the tensile plot is to choose an identical force value for the two sets of yarns, as a visual estimate of when the yarns’ response begins to differ from that of de-crimping. With a tension value of 0.7 N, crimp is 2.66 % in the warp and 1.68 % in the weft; with a force of 1 N, crimp is 2.89 % in the warp and 1.81 % in the weft. As can be seen, the mechanical crimp tests leave some room for interpretation. Nevertheless, all errors are of the same order of magnitude.

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[13] Sample yarns were 600 mm long. A certified twist meter was not available but a careful manual and visual process is probably more precise, though it would not be suitable for industrial purposes.

[14] In this case the area describes the whole sample, which measures 10x10 mm.

[15] Three yarns in each direction, 140 mm long, tested at the speed of 10 mm/min.

Table 2
Measures of Twist Per Meter in warp and weft, and weighted mean values. The values in blue are the highest.

Warp	numerosity			number of twists per meter (TPM)			
sample name	S	M	L	S mean	M mean	L mean	weighted mean
D. Malinconico	2	7	4	438.7	144.3	134.3	**186.5**
B. d'Agesci	1	13.7	4	515.6	184.7	174.0	**200.1**
R. Postiglione	1	6	1	310.3	221.1	196.9	**229.2**
J. Gélibert	1	22	1	280.1	244.9	193.1	**244.2**
18th c. lining canvas	2	3	2	319.0	235.0	136.8	**231.0**
L. A. Auguin	2	21	2	357.5	330.5	228.3	**324.5**
L. Alleaume	2	18	4	208.6	230.0	140.4	**213.3**
C. Müller	5	20.3	6	423.3	407.7	158.3	**362.4**
A. E. Fragonard	1	10.7	2	394.2	186.3	153.4	**196.7**
Basket weave lining canvas	2	14.3	3	183.6	156.3	176.8	**162.1**
Pattina lining canvas	2	6	1	371.6	281.4	196.1	**291.9**

Weft	numerosity			number of twists per meter (TPM)			
sample name	S	M	L	S mean	M mean	L mean	weighted mean
D. Malinconico	3	5	4	393.7	145.0	134.7	**197.9**
B. d'Agesci	2	9.8	5	293.0	289.3	163.7	**252.3**
R. Postiglione	1	5.5	2	201.3	150.0	85.7	**140.3**
J. Gélibert	1	16	1	234.1	297.5	192.1	**288.5**
18th c. lining canvas	2	4	2	185.5	218.9	141.9	**191.3**
L. A. Auguin	2	21.3	2	513.4	472.3	333.8	**464.6**
L. Alleaume	2	16.7	3	270.4	251.9	231.9	**250.8**
C. Müller	5	20	4	473.0	385.8	241.8	**381.0**
A. E. Fragonard	1	7.3	3	268.5	131.1	166.6	**152.6**
Basket weave lining canvas	3	11.3	3	249.5	261.3	229.3	**253.1**
Pattina lining canvas	1	7	1	358.8	174.7	177.1	**195.4**

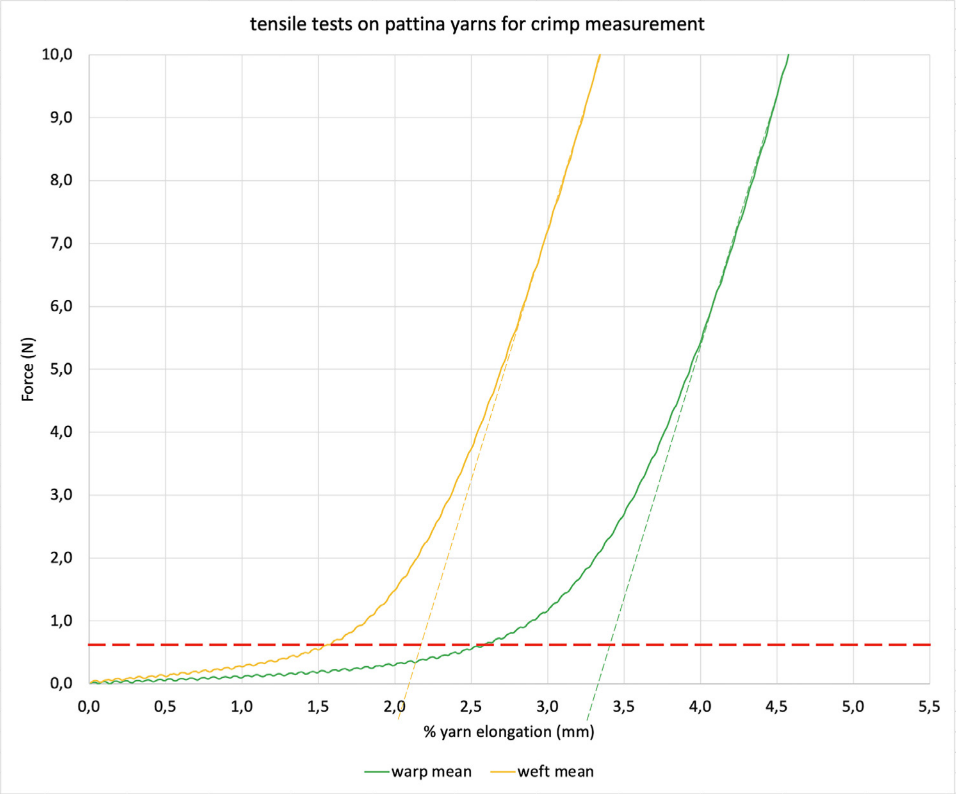

Fig. 7. Tensile tests on crimped yarns of the pattina lining canvas.

Table 3
Crimp measures in warp and weft, with averages and standard deviation values.

Crimp measures	crimp %									
sample name	warp 1	warp 2	warp 3	weft 1	weft 2	weft 3	warp mean	weft mean	warp st. dev.	weft st. dev.
D. Malinconico	10.35	9.44	13.55	3.66	4.18	5.02	**11.11**	**4.29**	*2.16*	*0.69*
B. d'Agesci	4.73	6.82	7.56	10.22	3.99	7.65	**6.37**	**7.29**	*1.47*	*3.13*
R. Postiglione	8.09	2.93	4.45	2.49	4.25	3.06	**5.16**	**3.27**	*2.65*	*0.90*
J. Gélibert	12.30	11.36	12.10	3.40	3.58	3.71	**11.92**	**3.56**	*0.50*	*0.16*
18th c. lining canvas	2.28	0.93	2.77	2.16	3.59	1.70	**1.99**	**2.48**	*0.95*	*0.99*
L. A. Auguin	17.67	13.78	7.44	5.80	3.87	4.28	**12.96**	**4.65**	*5.16*	*1.02*
L. Alleaume	9.71	11.82	12.56	6.54	8.62	5.11	**11.36**	**6.76**	*1.48*	*1.77*
C. Müller	11.82	8.49	10.48	4.96	6.47	5.66	**10.26**	**5.70**	*1.68*	*0.76*
A. E. Fragonard	8.78	8.21	7.81	2.66	3.40	2.47	**8.27**	**2.84**	*0.49*	*0.49*
Basket weave lining canvas	7.03	7.63	6.83	1.04	2.63	1.06	**7.16**	**1.58**	*0.42*	*0.91*
Pattina lining canvas	2.93	2.45	3.44	0.72	1.42	2.59	**2.94**	**1.58**	*0.50*	*0.94*

Crimp measurements are more invasive as they require the observation of yarns extracted from the specimen. Using the same yarns corresponding to the dimensional classes created for the TPM measurements would mean destroying the sample, as they would all be extracted for observation. A similar statistical treatment was therefore excluded, and yarns were extracted from the remaining parts of the specimen, outside the sample but close to the laser cuts. If compared with the twist measurement, the crimp observations involve a much larger section of the yarn (between 8 and 15 mm long, or 4–9 wavelengths depending on the width of the yarn), therefore each of them is an average per se. The method proposed here, based on the direct measurement of the crimped yarn on its image, is rather straightforward. As we have seen, its precision was validated in [20,21] and confirmed here using a comparation with mechanical tests results.

Results and discussion

The measurement methods proposed have been validated by comparison with established mechanical methods, on industrial textiles. The effort to propose new protocols was motivated by the fact that, after careful investigation, no reliable alternatives were found to be available for historical textiles. Within the framework of this methodological study, the amount of data collected makes it possible to approach the recurrence of features in historical and modern textiles. The values appear to be reliable and the level of error in the measurements commensurate with the intrinsic variability of the materials that are the subject of the study. The effects on the mechanical behavior of the textiles will become apparent when the samples are subjected to tensile tests using the biaxial tester [18]. It should be noted that, in the absence of the data obtained in this work, any mechanical information would be unrelated to quantitative descriptions of the textiles.

Twist values are inherently variable because they depend on the amount of fibers making up the yarn, their local flexural stiffness, and on the thickness of the yarn. When the twist is measured mechanically with a twist meter on long strands of new yarn from the same bobbin, local differences are compensated for in a process that averages the local differences in the final result. Therefore, twist measurements taken on the visible section of a yarn at the crossing point on the surface of the historical textile have a different starting point and are difficult to compare with the mechanical ones. Conti and Tassinari [10], in their experimental and methodological study, reported a measurement error of between 5 % and 15 %. The experience gained in the present research suggests that they were confronted with the intrinsic variability of the datum and with a high degree of unpredictability. The simple statistical method used here to obtain the weighted mean of the local values is therefore particularly relevant and produces a representative value, reduces the error and allows more robust comparisons. Looking in the detail of the results, and in particular at the number of TPM as a function of the yarn width classes in Table 2, we see that in no case do wider yarns (class L) have a higher number of twists than the thinner ones (class S). In 19 out of 22 cases the thinnest yarns have the highest TPM, in the remaining 3 cases the highest TPM value is found in the intermediate class (M). This confirms that, at least for the group of textiles in this study, selected to represent a spectrum of possibilities, thinner yarns are more twisted.

The variability of the crimp measurements is expressed by the standard deviation of the measurements on the 11 textiles examined, which has an average value of about 1 %. Crimp variability along the yarn is also causing the above-mentioned difference with the simulated crimp tester, where the results obtained on samples of about 10 mm with 140 mm strands of yarn are compared. The measured crimp values show a relevant consistency in the fact that 9 of the 11 cases studied have a higher crimp value in the warp than in the weft. This is particularly interesting because it is a constant for both the historical, naturally aged fabrics and the two modern industrial fabrics used as tally. Furthermore, similar results are found in the available conservation science literature [22] and [8]. In [20], the 30 modern canvas samples described[16] show higher warp crimp in >80 % of the cases. A correlation between a higher crimp and the warp direction is confirmed at the present state of the research.

Conclusions

The twist and crimp measurement methods proposed here contribute to the general knowledge of the woven structures, and appear to be particularly useful for historical textiles and for the lining canvases. They also reveal recurring characteristics in the yarns, the higher crimp in the warp direction and the higher TPM in the thinner yarns. The methods are based on relatively simple procedures and equipment, requiring only common skills and a good degree of awareness and accuracy. The goal of making the procedures affordable and widely available to the conservation community appears to have been achieved, and the authors are available to provide further assistance.

List of terms

Textile fiber. A material that is long, thin, and flexible, with a length at least 100 times its diameter, and is capable of being spun into yarn.

Yarn. A continuous strand of textile fibers spun in a form suitable for weaving. It can be single or plied, when consisting of two

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[16] See Table 4, page 1094 in [20].

or more yarns twisted together. All our specimens were woven of single yarns.

Warp. The set of lengthwise yarns that are held in tension on a loom during the weaving process.

Weft. The set of crosswise yarns that are interwoven with the warp yarns on a loom to create a woven fabric.

Twist. The spiral arrangement of fibers around the axis of a yarn, obtained by spinning, providing cohesion and stiffness to the yarn.

TPM. Turns (or Twists) Per Meter. The number of twists inserted in a meter of yarn. It is a measure of the twist intensity.

Twist angle. The angle formed between the helical path of the twisted fibers and the axis of the yarn. It is measured in degrees (°) and is at times used as a synonym of TPM, though it only provides a semi-quantitative information because it is not correlated with the yarn width or diameter. It can be used for comparisons only between yarns that are otherwise very similar and only different for the twist intensity.

Crimp. The waviness or curls imparted to the warp and weft yarns of a fabric by their interlacing during weaving.

CRediT authorship contribution statement

Antonio Iaccarino Idelson: Conceptualization, Methodology, Resources, Investigation, Validation, Writing – review & editing. **Otto Bergsma:** Supervision, Writing – review & editing. **Roger Groves:** Supervision, Writing – review & editing.

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