Animated Linen: Using High-twist Hygromorphic Yarn to Produce Interactive Woven Textiles

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ABSTRACT
HCI research has demonstrated that textiles have interactive potential, with the ability to transform or self-shape, whether through material, structure, or the addition of non textile elements. Many materials for developing interactive or animated textiles – textiles which change during use – are fossil fuel-based, require electricity for activation, or are only available in small quantities. In this pictorial we present our exploration of high-twist linen yarn as an actuator material in woven textiles. Through experimental design research, we have defined key parameters affecting use of the material, and identified combinations of material and structure producing contrasting textile movement. The resulting woven textiles may be activated by spraying with water, or in high humidity, and the actuation is repeatable after drying, offering multiple modes of interaction. We offer proposals for HCI applications for the animated linen yarn, alongside a guide to facilitate producing and designing animated woven linen textiles.

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Linen; high-twist yarn; weaving; animated textiles.

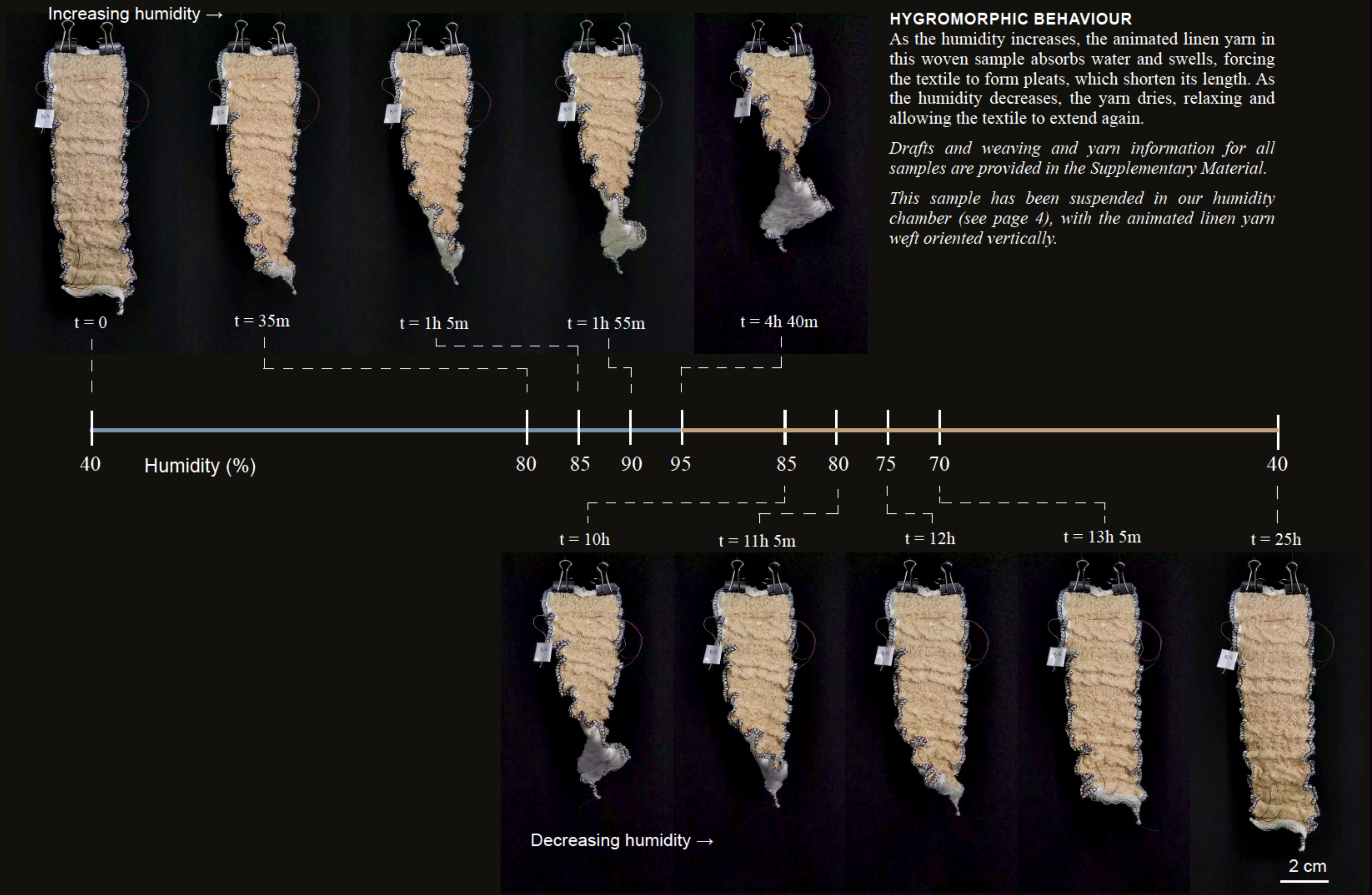
CSS Concepts
• Human-centered computing~Human Computer Interaction (HCI)

INTRODUCTION
Textiles, as soft and flexible materials, offer numerous possibilities for interaction, becoming "Animated Textiles" when they are designed "to generate novel responsive behaviour and interactions" during use [3]. We use the term "animated" to bring attention to the ability of textiles to change shape and texture based on their design and structure, as opposed to changing in response to electronic input, as may be assumed of interactive textiles. Textiles may be animated through their structure [4,1], materials [14,36], or through the integration of metallic threads, yarns, or other components [10,17,28,29]. In woven textiles, interactive structures typically require specialised knowledge [4,8], while added components often introduce sustainability issues at end of life [24]. Furthermore, commercially available materials for developing woven animated textiles are limited and often fossil-fuel based [24].

Therefore, we have explored the potential of high-twist linen yarn to produce woven animated textiles. Linen yarn, made from flax plant bast fibres, has a low environmental impact during production, and is fully biodegradable at end of life [21]. Conventional linen yarn is readily available, and the twisting process to transform it into animated yarn can be performed by hand – with a spindle or spinning wheel – or a twisting machine. As this process requires no chemical, surface, or heat treatment, the yarn remains entirely plant based and biodegradable.

Linen fibres swell as they absorb moisture [25]. In a high-twist yarn the fibres are locked into place, and their swelling is transferred to the yarn. Textiles woven with this 'animated' linen yarn may exploit this property and exhibit hygromorphic behaviour: changing form when wet or exposed to high humidity, and relaxing in dry conditions. Furthermore, the animated linen yarn has interactive properties whether used in simple woven structures, or complex multilayered textile-forms, increasing its accessibility.

This pictorial presents our exploration of animated linen in woven textiles, conducted through experimental design research [30,34], a form of research through design. We have explored how variables of twist angle, float length, and weave structure affect the hygromorphic behaviour of a textile. Alongside the results of this research, we include an introduction to yarn terminology and proposed applications for animated linen textiles. Finally, we provide a guide to enable other researchers, designers, and practitioners to make large quantities of animated linen yarn in their own research spaces.



HYGROMORPHIC BEHAVIOUR

As the humidity increases, the animated linen yarn in this woven sample absorbs water and swells, forcing the textile to form pleats, which shorten its length. As the humidity decreases, the yarn dries, relaxing and allowing the textile to extend again.

Drafts and weaving and yarn information for all samples are provided in the Supplementary Material.

This sample has been suspended in our humidity chamber (see page 4), with the animated linen yarn weft oriented vertically.

RELATED WORK

Textiles have been applied in HCI since at least the late 1990s [26]. There are many approaches that use existing textiles as a substrate, adding elements such as coatings [32], shape memory alloys (SMA) [5,27], electronic components [2], and pneumatic actuators [22]. Alternatively, interactive materials may be integrated into the textile structure as it is constructed, as seen in electronic and smart textiles [9,29,35].

Animated and actuating textile materials

Heat-activated shrinking yarns are commercially available, readily incorporated into both knitted [36] and woven textiles [3], and produce rapid shape change. However, the transformation is one-way, reducing the opportunity for repeated interaction, and the yarns are typically fossil-fuel based polymers. SMA springs may be integrated in textiles through knitting [20] or weaving [35], and offer reversibility, although they require electrical activation, are usually only available in small quantities, and are expensive to use at scale. HCI research has produced a number of alternative reversible actuating materials suitable for weaving or knitting, including: liquid crystal FibeRobo [14], activated by heat, either electrically from the body; fluidic actuator OmniFiber [19], which requires a pneumatic controller; and ModiFiber [15], a silicon-coated coiled nylon actuator, heated electrically to activate. Of these, only FibeRobo is produced in continuous lengths.

Hygromorphic linen

In contrast, Scott's [33] Responsive Knit demonstrates reversible hygromorphic shape change with a combination of material and structure developed through biomimicry. The combination of a high-twist linen yarn, which swells when wet, with squares of reversing stitch direction, enables shape change within the textile. In weaving, high twist linen yarn in specific weave structures has been used to create self-pleating textiles, potentially as early as 4,500 years ago in Ancient Egypt [31]. Recently, water-responsive helical artificial muscles from linen yarn have been demonstrated and proposed as a smart textiles material [37]. However, the artificial muscles used a surfactant treatment to improve performance, and, as helical coils, are unsuitable for making textiles.

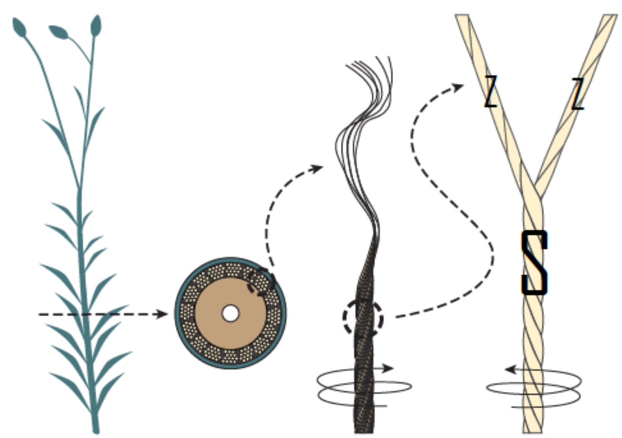
We hypothesised that high-twist linen yarn could be used to produce interactive, reversible hygromorphic woven textiles. Through making our own animated linen yarn by adding twist to commercial yarn, we aimed to explore its design variables, and suggest it as a suitable material for animated textiles [3].

YARN CONSTRUCTION AND TERMINOLOGY

Linen yarn construction

Linen is produced from the bast fibres of the flax plant. These are groups of extremely long cells with thick, cellulose-based cell walls, which provide strength to the stem of the plant [16,25]. The fibres are separated from the rest of the plant through retting, scutching, and hackling before being spun into yarn [18,23]. Because linen is a natural fibre, variation of strength and thickness occur both within a yarn, and between batches of yarn.

Yarn is produced by twisting – spinning – fibres together to create a continuous length. This results in a 'single' yarn. Multiple single yarns can be twisted together to create a plied yarn, which is thicker and stronger than a single yarn [12,31].



From left to right: the flax plant; a cross-section of its stem, showing the location of the bast fibres; separated fibres are spun into a single yarn; two single yarns, each with Z twist, being plied into a yarn with S twist.

Yarn terminology

Metric count (Nm): Yarn count systems describe the density and number of plies of a yarn. The metric count is defined as the number of kilometres of single yarn per kilogram. It appears in the form "Nm X/Y", where X specifies the single yarn count, while Y specifies the number of strands of single yarns (plies) in the finished yarn [6].

Twist angle: Yarn twist is measured by the angle it makes with the length of the yarn. Twist may have a low twist angle (below 10°), medium twist angle (10°–25°); or high twist angle (25°–45°) [12,31].

Twist direction: The direction of twist in a yarn is designated as 'S' or 'Z'. S twist yarns are twisted anticlockwise while Z twist yarns are twisted clockwise. This creates a diagonal line along the yarn's length, either \ (S) or / (Z). Most plied yarns are balanced yarns, where the singles are twisted in one direction, and plied together in the opposite direction, balancing the twist of each process against each other [12,18].

Two Nm 21/3 yarns with S twist: on the left, twisted to 15°, on the right, twisted to 35°.

METHODS AND TOOLS

Twisting

Twist may be added to a single yarn, when plying single yarn together, or added to a plied yarn. We used commercial linen single yarns, using the plying process to add twist. The yarns were from an existing supply, and did not have manufacturer or supplier information. We used only Z twist single yarns, as we were unable to source S twist singles. Yarn count was estimated by weighing five 5 metre lengths of each yarn, and taking an average, before calculating the Nm count.

We used the twist angle calculation below (derived from Richards [31]) to determine the amount of twist to add to our yarn: tpcm is twists per centimetre, and m/kg is the total yarn density in metres per kilogram. Therefore, the twist angles of our yarns are a calculated, indicative angle, not a measured one.

$$tpcm = \frac{\tan(twist\ angle) * 0.255\sqrt{m/kg}}{\pi}$$

We twisted the yarns using an Agteks DirecTwist C6" twisting machine. Tension on the yarns feeding into the twisting machine was maintained using one Iro Star G2 pre-winder per cone. Since this equipment is not readily available, we include in this Pictorial a DIY method for twisting yarns by hand with a spindle or spinning wheel (see page 11).

Weaving

Animated linen yarn can be woven on any loom, as the weave structure has less impact than the yarn twist. It is ideally suited to handweaving, which produces closed selvedges. It may be woven successfully on industrial power looms, but the cut selvedges produced by most such looms will allow the yarn to untwist over time, reducing actuation strength.

We wove our samples on an ARM computer-controlled handloom with 24 shafts, warped with Nm 50/2 bleached cotton at 32 ends per cm (epcm), and a TC2 computer-controlled jacquard handloom, warped with Nm 34/2 organic unbleached cotton at 24 epcm.

The cotton warps were selected as they were softer than the animated yarn, allowing the animated linen weft yarns to move freely. As both cotton and linen are cellulose fibres, this produced mono-fibre, biodegradable textiles.

Weave structures

We have used mainly weft-faced satin weaves, which have long floats and evenly spaced binding points [12,18]. Our experiment testing float lengths and weave structures showed that any weft-faced weave structure with floats of more than 2 mm, and less than 12 mm could be effective, although we used weaves with floats of around 7 mm.

When weaving with multiple wefts in the same row (as in the checked examples on pages 7, 8 and 10), the wefts were clasped together at the edge of each check, rather than carried across the whole width.

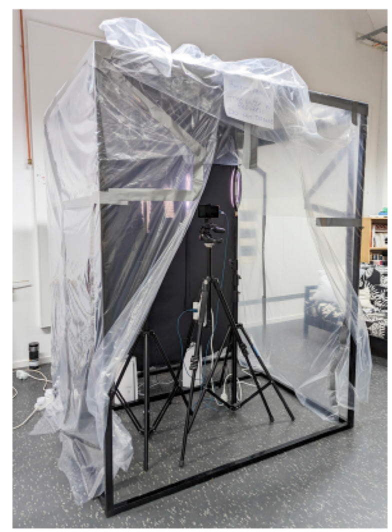
Activation

Misting the textiles with water in a spray bottle enabled instant activation. Laying samples flat enables the use of weights on the edges to transform a rolling actuation into a pleating actuation, while pinning them to a wall with the weft vertical allows them to relax more fully under gravity. Full relaxation takes 10–20 hours, which is much longer than the drying time (1–2 hours). Since linen creases easily, we found that a textile only needed be activated with weights two or three times for future activations to pleat even when unweighted.

We also built a simple humidity chamber, approximately 1.5 m wide and deep by 2 m high. We used two Proklima 20W ultrasonic humifidiers to increase humidity, and opened the door flap of the chamber to decrease humidity to ambient levels. Chamber humidity was measured with a ThermoPro TP49BW thermometer/hygrometer.

Twisting. The pre-winders (in the foreground) were necessary when twisting Z single yarns into Z plied yarns, as the plying twist would otherwise travel down the yarn, causing knots between the cone and the twisting machine.

Weaving on the TC2. We wove multiple samples across the width of the loom to speed up weaving and reduce yarn consumption. When combining S and Z twist yarns, this meant a lot of shuttles!



The humidity chamber, ready to be closed up and humidified. With two ring lights and a smartphone to record timelapse video.

Animated linen yarn

There are two factors that produce actuation in our animated linen yarn. The first is their high twist angle, between 20–40°, with lots of free energy in the yarn construction.

Increasing twist angle requires adding extra energy into the yarn through the twisting process. This energy, in excess of what is required to hold the yarn structure together, makes the yarn unstable. It will attempt to reach a lower energy state by untwisting, if one end is free, or by folding and twisting on itself, if there is slack in a length of yarn. When the yarn is woven into a textile, the yarn can no longer move itself to reduce energy, but may have enough energy to curl the corners of the textile, or even cause it to roll.

The other is the nature of the linen fibre. Flax bast cells, chains of which make up linen fibres, are unusual because they have an extremely thick cell wall, containing primarily cellulose, and an extreme height:width ratio of over 1,000 [16,25]. The cells, and therefore linen fibre and yarn, swell as they absorb water. When a linen yarn with a large twist angle absorbs water, the swelling pushes on the twist, increasing the energy in the yarn.

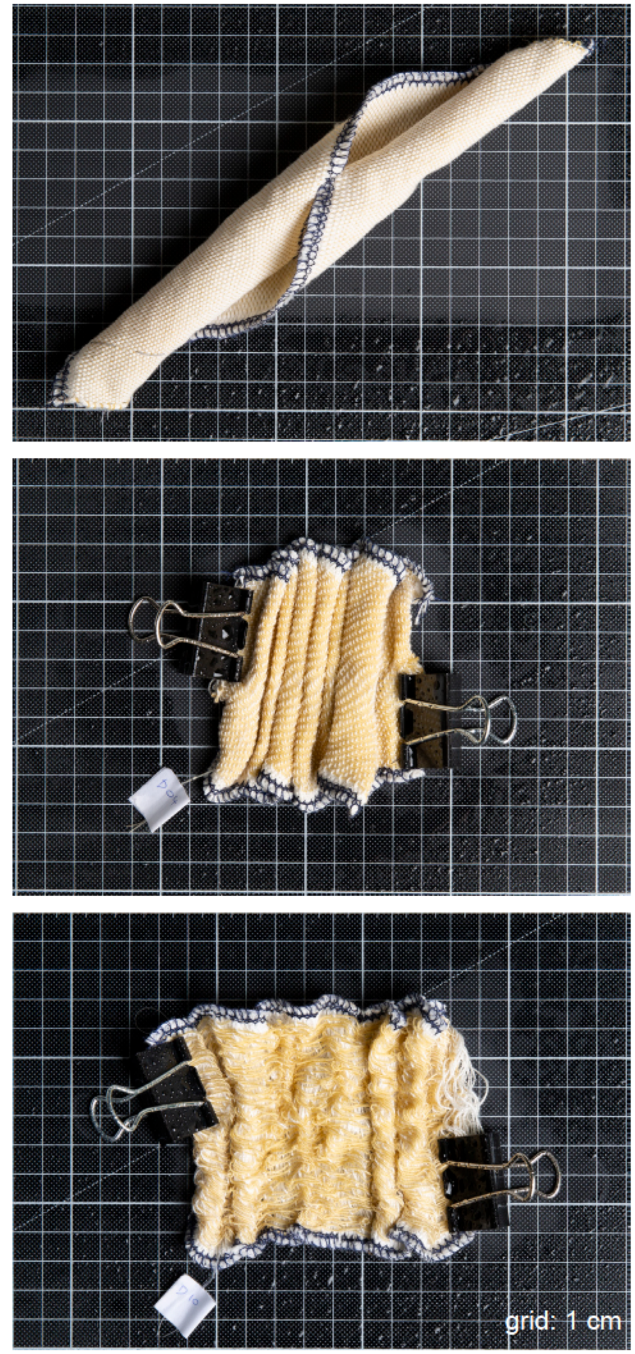
When a textile is woven with animated linen yarn and activated with water, the energy of the fibre swelling is added to the twist energy, providing enough energy to move the textile. If the textile is woven tightly, the yarn can only release energy by rolling the textile in the opposite direction from the yarn twist – this acts to straighten out the yarn locally, relieving the tension of the swelling pushing on the tight twist.

If the textile is woven more loosely, and prevented from twisting (we weighted the twisting corners with foldback clips), the yarn will untwist locally, putting pressure on the textile surface, and causing it to pleat. If the weaving is very loose, the yarn will come out of the weave structure and spiral on the textile surface. This reduces the amount of energy available to pleat the textile, resulting in less shrinkage.

Nm 21/3 25° Z twist yarns showing the different behaviours when under tension (top), cut and one end released (middle), and tension released (bottom).

Nm 21/3 25° Z twist yarn when dry (left) and wet (right).

Nm 21/3 20° Z twist yarn woven in a textile, showing swelling and movement when the yarn absorbs water. The camera has not been moved between photos.



Right: Nm 21/3 20° Z twist yarn woven as weft in a textile, rolling when tightly woven (top), pleating when woven loose enough to allow the yarn to untwist and cause pleating (middle), and reduced pleating when woven loose enough for the yarn to escape the weave structure and spiral on the textile surface (bottom).

Weave structure float length. Left to right: 0.8 mm, 1.3 mm, 2.1 mm, 2.9 mm, 3.8 mm, 7.9 mm, 9.6 mm, 12.1 mm, 14.2 mm, 17.1 mm. Yarn: Nm 21/3 20° Z twist.

TESTING THE SHAPE-CHANGING PROPERTIES OF ANIMATED LINEN

Yarn structure and weave structure

We tested the effect of twist angle and direction, weave structure and float length. This revealed that the twist angle of the animated linen yarn has the most impact on the hygromorphic properties of the textile, while weave structure has the least impact. The twist direction controls the direction in which the textile twists or rolls, moving to release the yarn twist. Weave structure float length below 2 mm prevents pleating, while floats above 14 mm allow the yarn to escape the weave structure and spiral, reducing the pleating effect. Samples with warp-faced weave structures take longest to activate, as the moisture must soak through the warp to reach the weft.

These samples have been hung on a wall with the weft oriented vertically, and sprayed with water to activate.

Left: S twist yarns; right, Z twist yarns. Twist angles of 5–40° in 5° increments. The Z twist yarns are animated at a lower twist angle, because only Z twist single yarns have been used – in the S twist yarns, some energy is lost as the Z twist singles are twisted in the opposite direction during plying.

Weave structures. Left to right: three samples with different satin weave structures, a herringbone twill, stripes of weft- and warp-faced satin, a large basketweave, eight samples with different twill weave structures. Yarn: Nm 21/3 20° Z twist.

Combining S+Z twist yarns

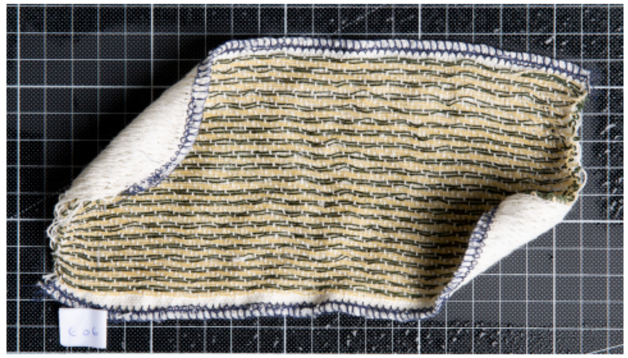
We hoped to create textiles which pleated without needing to be weighed down during activation by combining S and Z twist animated linen yarns in a single textile. Initially, we tested a compound weave structure, which gave us an S side and a Z side on the same textile, and a series of samples with stripes of S and Z twist yarn in different widths.

The compound sample had two behaviours due to the imbalance in energy between the yarns: the Z twist yarn proved to be stronger than the S twist yarn. When wet on the Z twist side, the textile would curl, however when wet on the S twist side, the textile would only ripple, as the energy of the activated S twist yarn was insufficient to overcome the competing energy of the Z twist yarn.

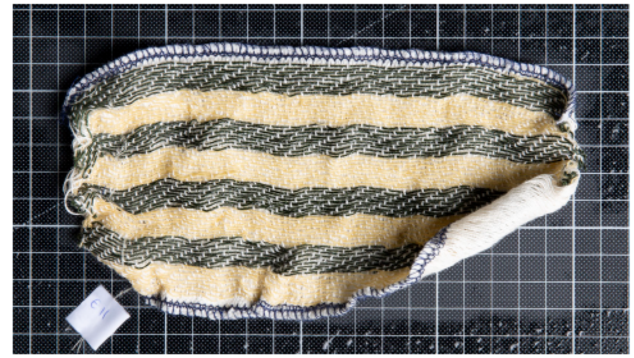
The striped samples showed very little shrinkage, curling only a little at the corners. The opposing energy of the S and Z twist yarns in this configuration proved to mainly counteract each other. However the sample with the largest stripes showed a small ripple effect. This suggested that combining S and Z twist yarns would be most effective in larger blocks.

Combining the yarns in a checked pattern demonstrated the uneven forces produced by the two yarns. It also revealed a new morphology produced by the textile's hygromorphic transformation. Here, the energy from each yarn was able to be released through the textile, not cancelled out as in the striped samples, but interacting at the boundary of each check to prevent the textile from forming a simple roll.

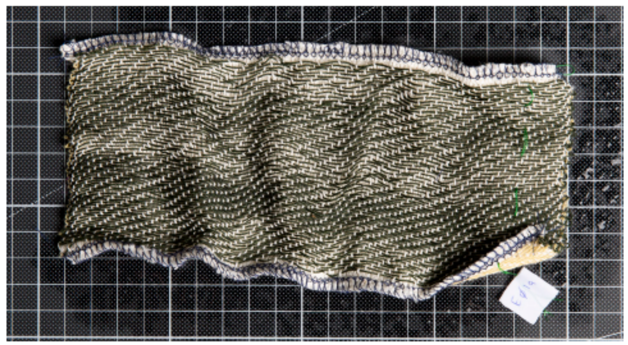
These samples were laid flat with weft oriented horizontally and sprayed with water to activate. The background grid is in centimetres.

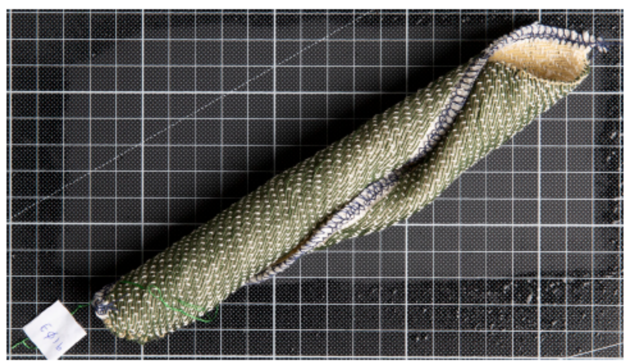


Stripes two wefts high, of S twist yarn and Z twist yarn. All yarns this page: Nm 20/3 30° S twist (green) and Nm 21/3 25° Z twist (yellow).



Stripes nine wefts high, of S twist yarn (green) and Z twist yarn (yellow), showing gentle ripple effect, especially at the edges.



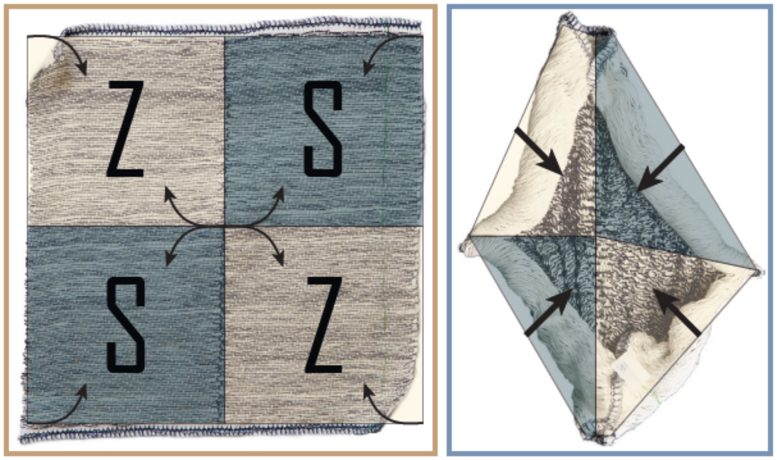


The compound weave structure with an S twist yarn on one side (green) and a Z twist yarn on the other (yellow), demonstrating its different behaviours when activated on each side.

The sample with S (green) and Z twist (yellow) yarns in a checked pattern showing uneven yarn energy when activated, producing a new animated morphology. Inset: before activation.

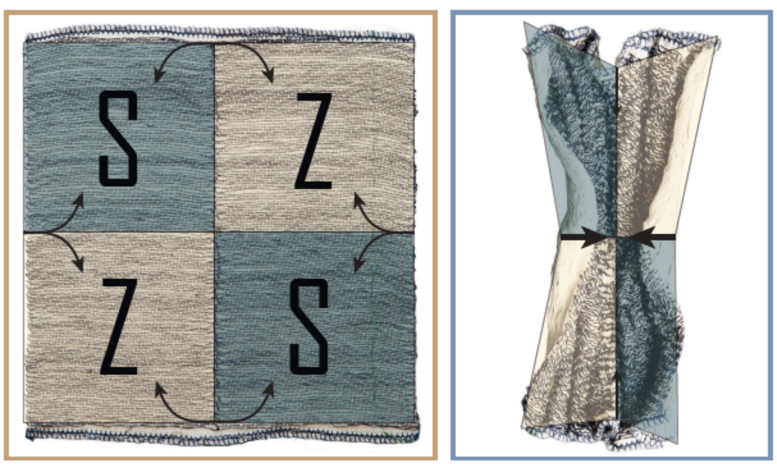
Combining S+Z yarns of equivalent strength

We were able to produce S and Z twist yarns with equivalent actuation strength by twisting the same yarn to 40° S twist and 30° Z twist. Inspired by the earlier checked example, we discovered that, depending on the arrangement of S and Z yarns, two different behaviours could be produced: one in which all four corners curled towards the centre, and another in which the twisting force is converted into weft-ways shrinkage. In this second arrangement, the textile forms an hourglass shape when activated, which relaxes when dry back to a rectangle.



Above: when S+Z checks are arranged so the twisting forces are at the outside corners, all four corners roll inwards.

Below: when the S+Z checks are arranged so the twisting forces are on the sides, the result is weft-ways pleating and shrinkage



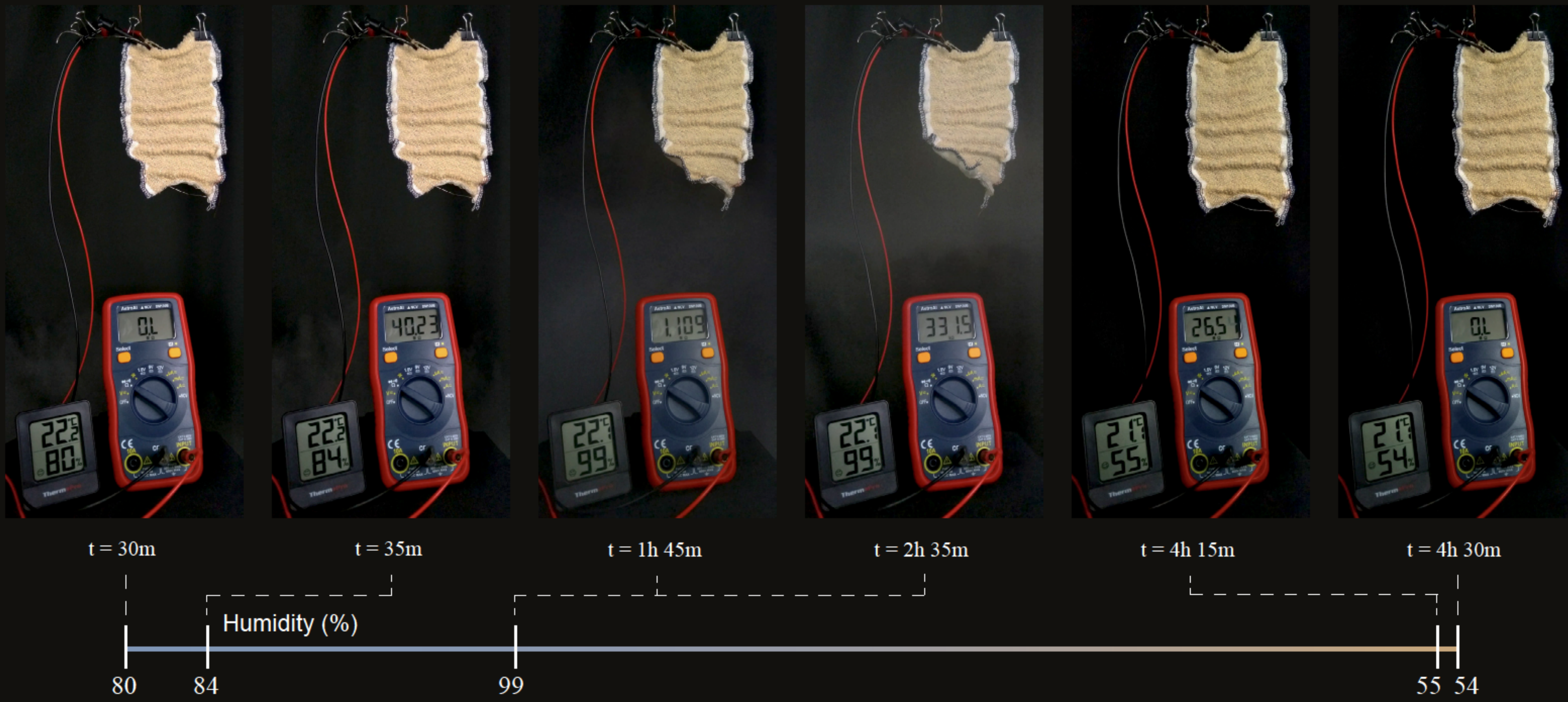
PROPOSED APPLICATIONS

Analogue humidity sensor for plants

Here, we have used the second checked arrangment to create an analogue sensor to indicate when a plant requires misting. When the hourglass shape has relaxed and the warp side is no longer visible along the edge, it is time to mist again.

Loom: TC2 jacquard
Warp: Nm 34/2 organic cotton at 24 epcm
Weft: Nm 21/3 animated linen, 30° Z twist and 40° S twist at 8 ppcm

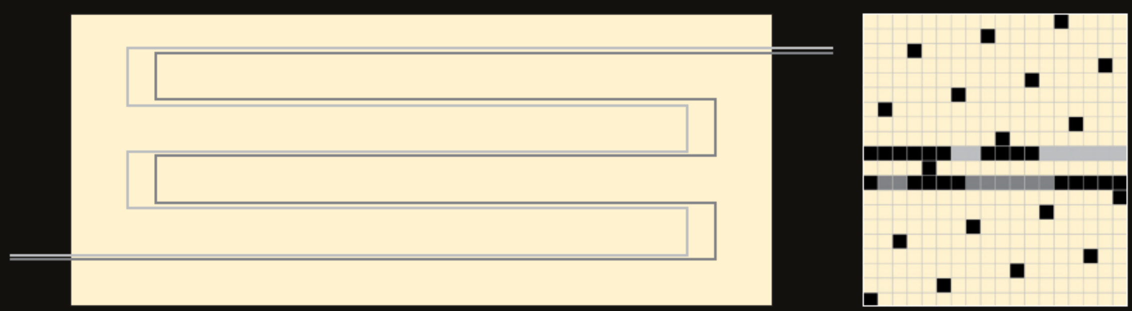
Left, top: the sensor is fully relaxed – the plant needs misting.
Left, bottom: the plant and sensor have been misted, and the sensor has activated, warp side curling around to the front.



Electronic sensing

The animated linen yarn can be woven alongside conductive yarn to construct e-textile sensors. In this sample, two conductive yarns were woven with one pick of animated linen in between them. When exposed to moisture in our humidity chamber, the water absorbed by the linen fibre bridges the gap between the conductive yarns. As the moisture content of the textile increases, the resistance drops. As the textile dries, the resistance increases, until the bridge disappears and there is no longer a connection between the conductive yarns.

Loom: TC2 jacquard
Warp: Nm 34/2 organic cotton at 24 epcm
Weft: Nm 21/3 animated linen, 20° Z twist at 8 ppcm
Conductive wefts: Karl Grimm High Flex 3981 7X1 silver and copper



Left: diagram showing the paths of the two conductive yarns through the woven sensor.
Right: weave draft showing how the two conductive yarns (in light and dark grey) are placed between the linen picks.

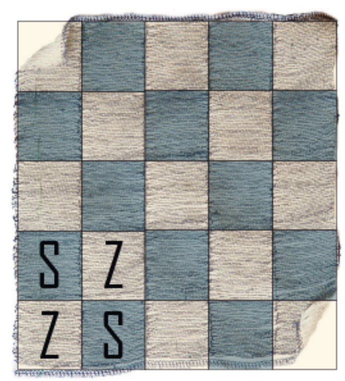
Weather-sensitive garments

When S and Z twist animated linen yarns are combined into a larger checked pattern, activation causes peaks and valleys where the textile twists towards or away at the corners of each block. This causes the textile to adopt a semi-regular wavy texture when activated with moisture, which flattens out as it dries.

As textiles are associated with garments and soft furnishings, objects that we touch every day, we wondered about the experience of wearing animated linen. We created a mock-up of a partial sleeve to illustrate the potential of animated linen for producing weather-sensitive garments, which would be activated by both rain and high humidity. Snug around the wrist, and loose around the forearm, the sleeve allows the wearer to haptically experience a hygromorphic transformation.

A first-person perspective of wearing the animated linen sleeve:

The inside is soft and smooth, from the long cotton floats of the warp. On the outside it feels crisp and irregular, bumpy where the linen weft has not fully straightened from its last activation. When I spray it with water, I feel the cool spray on my exposed skin, and sparse little droplets making it through the loosely woven fabric. Then, as the linen absorbs the water, I can feel the sleeve moving over my skin. It is a tightening sensation, a gentle pressure, almost tingly. I am being clasped ever so slightly tighter by the sleeve, a feeling in strange contrast to my other arm, unclothed. I begin to feel like I can sense my pulse in my arm. Touching the damp outside it feels almost hard, bumpy, lumpy, leaving moisture on the skin of the touching hand. I can feel the pressure of my hand through the sleeve, but it is unlike the feeling of the sleeve animating. I wonder what it would be like to wear a whole outfit like this, and dance in the rain.



Loom: TC2 jacquard
Warp: Nm 34/2 organic cotton at 24 epcm
Weft: Nm 21/3 animated linen, 30° Z twist and 40° S twist at 7 ppcm

DIY WITH ANIMATED LINEN

We believe our study of animated linen yarn offers a compelling case for the adoption of this material in interactive woven textiles. While we have made use of high-tech twisting and weaving equipment, the fundamental techniques used – spinning and weaving – may be undertaken with very basic tools. Industrial machines increase the speed of these processes, aiding scalability. However, they may also provide a false sense of precision: linen is a natural fibre, and there are variations in even industrially spun yarns – changes in strength and fibre size within and between individual plants and crops, as well as breaks and splices between lengths of fibre. Therefore, each yarn will have slightly different energy and behaviour along its length regardless of method of twisting. Furthermore, the loose weave structures used here allow warp and weft to move against each other. That this movement does not affect the hygromorphic behaviour of the textile indicates that a simpler, less precise tool for weaving, such as a frame or pin loom, could easily be used.

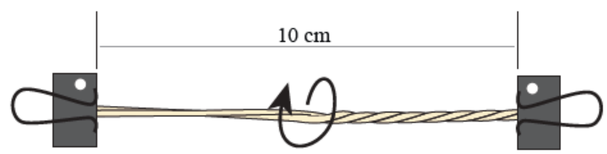
Therefore, to facilitate adoption of animated linen by other researchers, designers, and practitioners, we present a guide to twisting and weaving animated linen yarn and hygromorphic textiles with minimal equipment.

Twisting

When twisting your own animated linen yarn using a spindle or spinning wheel, you can add twist to an existing yarn, or create a new yarn by twisting together multiple strands of singles or existing plied yarns.

We have adapted these instructions from those in *Weaving textiles that shape themselves* [31] and *Collapse weave: Creating three-dimensional cloth* [13] which were written for those familiar with spinning by wheel. We have added instructions for twisting with a spindle, and made explicit the instructions for using a spinning wheel. The notes below are our own.

- When selecting your yarn, avoid 'tow yarn', which has shorter fibres and will not have the same hygromorphic effect. Look for 'wet spun' or 'line linen'. Linen yarn sold for weaving should be fine, but linen yarn for knitting may not be.
- All yarns are different, so testing will be required to determine optimal twist angles and weave structures. When first testing a yarn, an angle of 30–35° is a good starting point.
- However, if you haven't tried making high-twist yarn before, starting at a twist angle around 15–20° will make it easier to get used to the process, as high-twist yarns are prone to tangling.
- It is easier to ply yarns in the opposite direction to the component singles (or plied) yarns: this is recommended when starting out.
- Linen is stronger and more pliable when wet, so you may find it easier to twist if you twist in higher humidity or lightly mist the yarn before twisting.



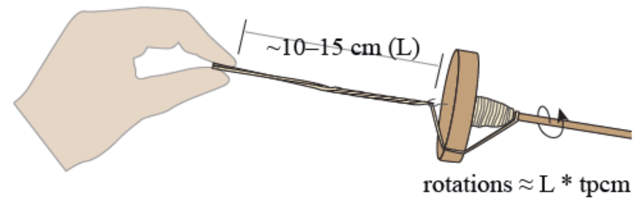
Adding twist to an existing yarn

Instead of plying together separate yarns, you can add twist to an existing commercial yarn. You can only add twist in the direction the yarn has already been spun or plied.

First, you need to determine the twists per cm already spun into the yarn:

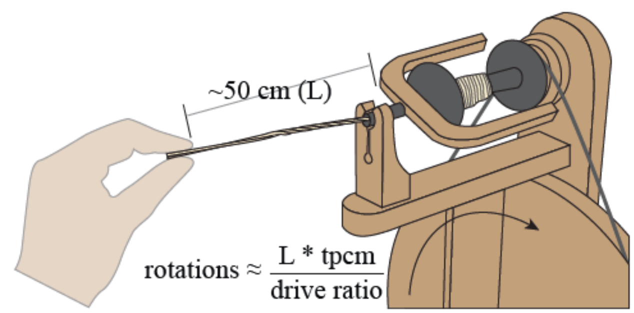
Take a length of yarn >10 cm, and place two clips on the yarn 10 cm apart. Mark one side of each clip. Untwist the yarn from one end only, counting each full rotation (the marks will help here). The yarn is fully untwisted when you can slide a pin between the strands or plies all the way from marker to marker. Repeat this process with new lengths of yarn at least four more times, take the average number of twists, and divide by 10 (the length in cm).

Subtract this number from the twists per cm required for your desired twist angle, to get the number of twists per cm you need to add to the yarn.



Twisting with a spindle

Attach the ends of the component yarns to the spindle. Firmly grip the yarns a comfortable distance from the spindle – perhaps 10–15 cm. Twist or spin the spindle, without changing the length of yarn, counting the rotations. When the twists are complete, wind the twisted yarn on to the spindle, making sure not to release tension until the length has been completely secured, and twist the next length.



Twisting with a spinning wheel

You will need to know the drive ratio of your wheel: the number of times the flyer or bobbin turns for each rotation of the large (drive) wheel.

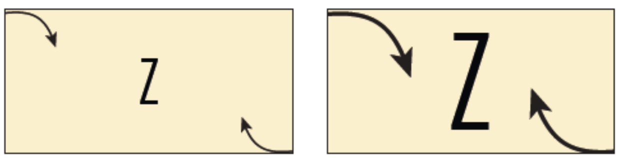
Attach the yarns to the bobbin. Measure a comfortable length from the bobbin to your hand – around 50 cm. Firmly grip the yarn, and spin the required twists into the yarn, without releasing or feeding it. When the twisting is complete, allow the length to wind on to the bobbin, without releasing tension. Grip the next length of yarn, and repeat.

Weaving

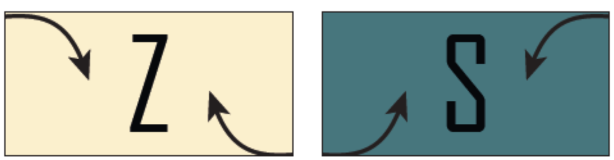
There are two important elements to consider when weaving with animated linen yarn: warp material and float length. The warp material should be softer and lighter than the animated linen weft, or it will resist the hygromorphic transformation. However, this is a variable that could potentially be exploited to control the amount or speed of the transformation. For the second element, float length, our tests indicated that float lengths of 2–14 mm, regardless of weave structure, are capable of producing rolling and pleating transformations. Therefore, even a simple frame loom could be used to weave a hygromorphic woven textile.

Designing

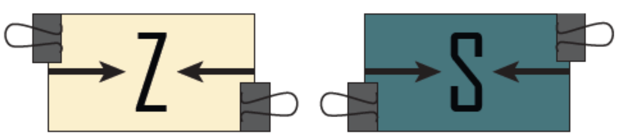
Given the above weaving constraints, the main variables when designing hygromorphic woven textiles are the twist angle and twist direction of the animated linen weft, as summarised below.



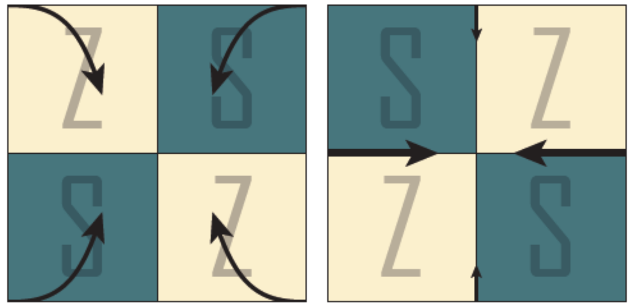
The greater the angle of twist in the yarn, the more the textile changes when activated.



The direction of twist in the animated linen yarn controls the direction of roll in the woven textile.



Weighting the curling corners during activation will change a rolling transformation into a pleating transformation.



Combining S and Z twist yarns of equivalent strength in checks produces different transformations when activated, depending on how the rolling forces are arranged.

For those who are interested in using AdaCAD [11] to generate weave drafts for use with animated linen yarn, a how-to documenting some of the samples from this pictorial is available at https://docs.adacad.org/docs/howtouse/examples/hygromorphic-linen or scan the QR code below.

CONCLUSION

In this pictorial we have presented our exploration of animated linen yarn, which we propose as a sustainable, biodegradable, and accessible material for interactive hygromorphic woven textiles in DIS. We have identified the main design variables for this material as twist angle and direction, and proposed applications for textiles woven with combinations of yarn in both twist directions. We have included a guide to twisting and weaving animated linen yarn, aiming to encourage adoption of this material by other researchers and practitioners.

Animated linen yarn is one method of developing interactive textiles without recourse to electrical or synthetic components. Instead, we have focused on the potential of textile structure and material itself to generate shape-change. Investigating the properties of this natural fibre, we have discovered a range of actuation modalities without needing to incorporate non-textile elements within our weaving. The inherent scalability of this material may lend it to body-based or architectural applications in the future, although further research is required to determine the limiting effect of scale and fabric weight on the hygromorphic transformation.

We hope that this work inspires others to explore and interact with the transformative properties of natural fibres, which have been overlooked in favour of synthetic and electronic smart materials. In fact, we believe this research demonstrates that natural fibres can be smart, too.

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