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Dynamic control of active shape memory textiles.

Abstract

The creation of controlled patterns of movement in woven textiles, through the integration of wire-form, nickel titanium (Ni/Ti), shape memory alloys (SMA), offers the potential to generate unique properties in this bi-material composite. The combination of two materials, one of which can be modified in regards to its stiffness and elastic behaviour, gives further latitude, for the textile designer to adapt, a combination of functional and aesthetic properties in constructed textiles. Limited research has been conducted to understand the relationship and behaviour of a NiTi wire integrated into a woven structure. The interaction between the SMA wire and the host structure is critical since most of the proposed applications require a transfer of force from the wire to the woven structure.

This paper first discusses how the interfacial relationships between the woven structure, supporting yarn and trained NiTi SMA wire, can be used to facilitate or impede direct as well as secondary levels of control in active shape memory textiles. Composite samples of different weave structures, supporting yarn, NiTi cross sections and finishes were investigated through subjective evaluations of visual and tactile properties as well as a series of bend and tensile tests. From these results a number of design principles are discussed and the potential development of applications across a number of disciplines. This paper will focus on potential medical and healthcare applications including the development of remotely controlled fastenings for situations where dexterity or movement is impaired, compressive garments able to provide even pressure for the stimulation of recovery for burns victims, and exoskeletal supports to aid the control of paralysed or weak limbs.

1 Introduction

The increasing range of technically advanced fabrics is seeing the use of textiles expand into ever more demanding and extreme environments. Textiles are being readily developed and integrated into applications as diverse as the CorCap™ Cardiac support device used to help stabilise an enlarged heart and geo-textiles used to reinforce and stabilise earthworks and landscaping. As well as developments in these new applications, areas such as aviation have seen a return to the use of textiles as a composite skin as well as major components in the structural frame work. Many applications now use textile composites to provide rigidity and strength to structures which is in contrast to their traditional properties of adaptability and fluidity. To date there has only been a limited development of textiles that can be actively controlled, switching between a drapeable fabric with a traditional hand and a material that can take on a number of pre-programmed semi ridged forms. The understanding and development of such a fabric has been the focus of a wider body of research of which this is a part.

1.1 Shape memory materials

Stimuli responsive shape memory materials (SMM) have received increased interest in recent years. Demonstrating the ability to change from a deformed shape to a pre-programmed shape as a result of being exposed to an external stimulus, SMM have been integrated into many applications (Honkala, 2006: 85) to control or sense changes in the material. Examples of control and sensing properties include, shape, position, strain, stiffness, natural frequency, dampening, friction, and vapour penetration. The shape memory effect is most often activated by a change in temperature or stress but can also be induced by magnetic or electrical fields, UV light, pH levels, and, in some cases, water. This change is not simply a form of thermal expansion or liquid absorption which can be seen in most materials, but is a switching between two stable states.

Developments of SMM fall into three main material types:

- Shape Memory Alloys (SMA)

    - Magnetic Shape Memory Alloys
- Shape Memory Polymers (SMP)
    - Shape Memory Gels
- Shape Memory Ceramics (SMC)

SMA and SMP have both been developed into fine mono filaments or wires suitable for integration into textile structures and the production of controlled patterns of movement. The active capabilities of SMA and SMP are very different with SMA demonstrating the potential to provide usable force and SMP demonstrating a loss in mechanical properties (Hu and Mondal, 2006: 107). At present SMP are outperformed by Nickel - Titanium (NiTi) SMA, in key areas required for active shape control, having a recovery force of about 1/100th that of NiTi and reaction times of between 25 and 60 seconds when compared to fractions of a second for NiTi.

1.2 Shape memory alloys

The first reference to the shape memory effect (SME) in a metallic material was observed in an alloy of gold-cadmium (AuCd) in 1932 by Swedish Physicist Arne Ölander. The breakthrough came in 1962 at the Naval Ordinance Laboratory in the United States when Buehler and his co workers discovered the shape memory effect in an atomically equal alloy of nickel and titanium (NiTi) (Hodgson et al., c2004: 1). NiTi SMA demonstrates an ability to change from a deformed shape to a pre-programmed shape as a result of being exposed to an external stimulus, undergoing a phase transformation in its crystal structure. When most metals are put under stress their crystalline structure slips or dislocates causing a non reversible plastic deformation. In the case of NiTi instead of slipping the crystal structure transforms between two reversible phases resulting in the shape memory effect. Under the umbrella of shape memory alloys, there are various forms the reaction can take, the main examples of these are:

- One way thermal shape memory; Materials that show shape memory only when heated and will hold that form until further deformed.

- Two way thermal shape memory; Materials that remembers different high temperature and low temperature shapes.
- Superelasticity shape memory; Material that shows an elastic quality as its structure changes due to deformation forces (twinned martensite). Return to the original geometry occurs due to the un-twining of martensite when the stress is released.

For one way and two way thermal SMM, independent thermal stimulus is required to achieve the transition temperature, this can be achieved generally by raising the ambient temperature, or selectively, by the resistive heating of the alloy. The superelastic SME does not require thermal stimulation, only the removal of applied stress.

1.3 Active shape control of NiTi composite textiles for rigid and flexible applications.

Application focused research on the integration of NiTi wires into woven structures has focused mainly on the development of ridged composite structures for vibration dampening, impact resistance and the ability to withstand lightning strikes (Boussu, 2006, Boussu et al., 2002, Foreman et al., 2007). The area of NiTi integration into flexible structures has been less widely explored but with notable research coming from Chan (Chan Vili, 2004, Chan Vili, 2007) and the development of a shirt by the Italian fashion house Corpo Nove (Corpo Nove, 2008) which can be 'Ironed' with warm air from for instance a hair dryer. Chan's research has focused on the spinning of NiTi composite yarns and the use of flexible NiTi composite textiles for interiors where the aesthetic properties can be maximised.

Construction methods and parameters have been investigated as part of these developments but limited data has been published and specifically the dynamic interfacial relationship between NiTi wires and textile structure has received little attention. The differing interfacial properties that can be achieved through the manipulation of a number of structural and material variables is of particular importance for the development of flexible composites. Through an understanding of this relationship, in addition to the primary direct control from the NiTi, to the textile structure a secondary level of control can be achieved. This secondary level of control is created by increasing or reducing the friction and there for the control from the wire to the woven structure. This additional level of control can also be used to facilitate, extend or impede the influence of the SMA wire across the textile in a similar manner to the wing of an insect (Sunada, 2008). Without direct muscular input or control beyond the root, structural differences across and insects wing enable it to react and adapt, achieving complex deflections as a result of air flow exerting pressure on the intricate wing structure.

2 Selection of variables

As part of a wider investigation into the relationship between NiTi wires and woven structures and supporting yarn this paper focuses on a selection of mercerised cotton and polypropylene (Duron CL) samples that underwent extraction tests of inserted NiTi wires using a computer controlled tensile / compression testing machines. The selection of a polypropylene yarn that was to be heat set prior to the extraction of the NiTi was intended to facilitate a strong bond between the woven structure and the NiTi wire as a comparison to samples using mercerised cotton. Variations in the weave type were also to be explored through the use of plain weave and 2/2twill weaves. As well as the yarn and woven structure the cross section and finish of the NiTi wire were explored and are summarised in Table 1.

Table 1 Summary of sample variables explored

Sample no.	Supporting yarn	Yarn count	epi	Weave	NiTi wire	Sample size
269B-274B	Mercerised cotton	2/60cc (70/2Nm)	66	Plain weave 2/2Twill	*b*	30x50mm
292B-297B			88			
556B-561B	Polypropylene	300den-72filaments.	54	Plain weave	*b*	30x50mm

573B-578B		(30/1Nm)	72	2/2Twill		
607B-612B	Mercerised cotton & Polypropylene warp. Mercerised cotton weft.	see above	63	Plain weave	*b*	30x50mm
624B-629B			81	2/2Twill		

Key;

epi Ends per inch calculated using Brierley's Theory of Empirical Maximum weavability

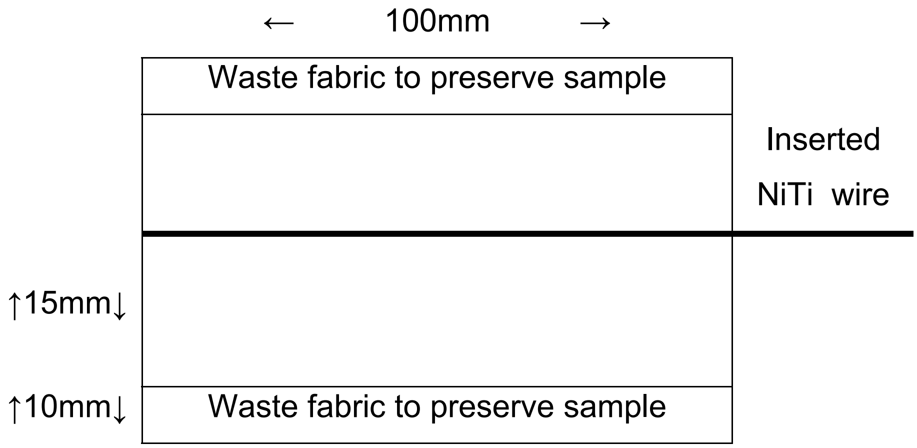
b - Selection of integrated components for extraction (Mercerised Cotton, 115µmØ, 152µmØ, 25x445µm, 50x420µm, 170x900µm NiTi wire).

In addition to the samples containing an integrated NiTi wire an additional sample was produced for each fabric type which contained an additional cotton weft yarn. These samples provided a baseline for both the bend and extraction tests to indicate the properties of a non NiTi composite.

2.1 Production of samples

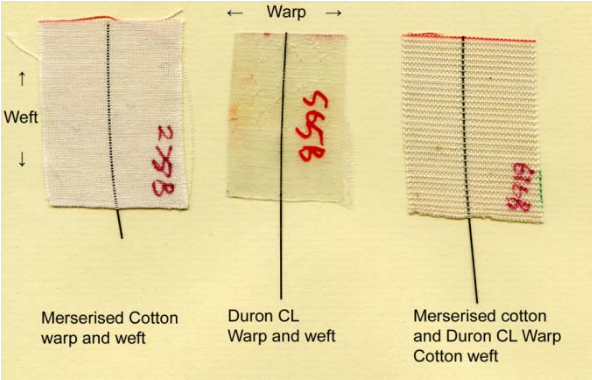
The composite textile samples investigated were woven on a 24 shaft Arm AG CH-3507 electronic dobby hand loom. This loom allowed for the quick adjustments to the weaving parameters and the accurate insertion of the weft yarn and NiTi due to the use of a sliding beater. As a result of earlier samples that investigated the insertion of the ‘springy’ NiTi wire it had been demonstrated that by slightly over setting the cloth, the coverage of the wire by the supporting yarn increased and the cloths tightness lessened, becoming a weft faced fabric. This produced a smoother cloth with the wire causing minimal distortion to the surface and also reduced weaving defects. The loom was setup in a straight draft on 12 shafts using an 18 epi reed with 3 and 4 ends alternately per dent for the plain weave samples and 4 and 5 ends alternatively per dent for the 2/2 twill samples. The samples were woven to a width of 30mm x 100mm with the NiTi wire inserted in the weft with 15mm of on either side. An additional 10mm woven on either side acted as waste fabric to preserve the integrity of the sample to be tested (Fig.1).

Fig. 1 Diagram of sample



After being removed from the loom all the samples were heat pressed using an A. Adkins Mk 6 heat transfer press. For this process the samples were placed between two sheets of PTFE coated glass fibre fabric and pressed at 200ºc for 20 seconds. This process was used to melt the polypropylene yarn (Polypropylene has a melting point of ~160°C) bonding it to the NiTi wire and cotton yarn (Fig. 2). After heat setting the samples were trimmed to 30mm x 100m for bend testing then to 30mm x 50mm prior to the extraction of the NiTi wire.

Fig.2 Examples of woven sample after heat treatment



3 Experimental

3.1 Bend testing

Bend testing was carried out using a Flexomiter (Fig. 3) to attain a bend angle for each sample. The bend angle of a fabric can be used as a guide to its rigidity and will demonstrate the effect the insertion of a NiTi wire will have on the fabrics handle when compared to other samples. Each sample was held in place on a fixed horizontal platform with 65mm extending over an angle adjustable shelf. Once set the adjustable shelf was lowered until the point the sample left contact from the self. At this point an angle reading was taken (Fig. 4).

Fig. 3 Flexometer with test sample

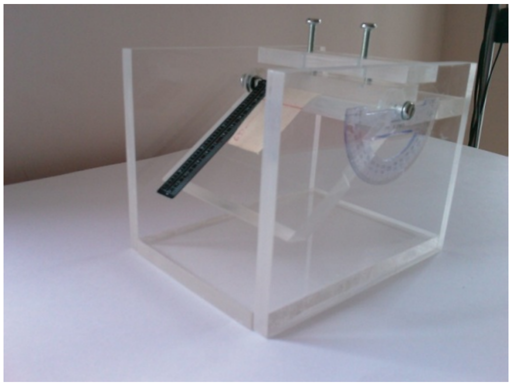
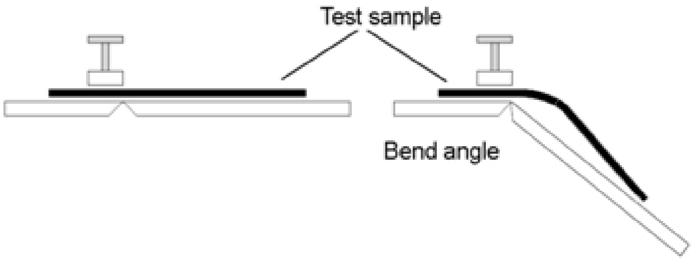


Fig. 4 Bend angle testing



3.2 Extraction testing

Extraction testing was used to investigate the dynamic friction and as such the relationship and mechanical interaction between the differences in the composite structures and inserted NiTi wires. Higher levels of friction between the inserted NiTi wire and woven structure would facilitate the direct transfer of force and there for shape change from the NiTi wire to the woven structure. Conversely a reduction in friction would reduce the shape transfer potential from the NiTi wire to the woven structure.

The extraction of the NiTi wire was performed by holding the sample (Fig. 5) between a set of clamps attached to an Instron model 1011 tensile and compression test machine. The handling and positioning of the samples in the clamps was critical to maximize the reliability of the results (Fig. 6). A special gig with a small recess was used for gripping the woven end of the sample, so the wire itself was not held allowing unhindered extraction from the woven structure. The free end of the wire which protruded from the sample was held in a conventional clamp. The extraction speed was set at 100mm per minute with readings recorded at a rate of 10 per second on a Schlumberger SI 3535D data logger attached to the Inston test machine. The readings were then exported to a PC Computer and into a Microsoft Excel spread sheet for analysis.

Fig. 5. Example of woven sample with inserted NiTi wire prior to extraction.

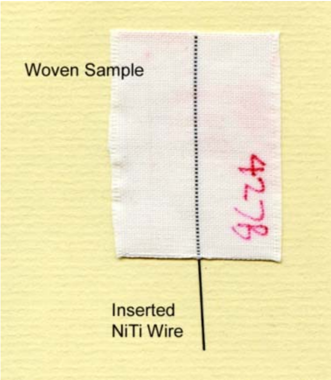


Fig. 6. Woven sample held in Instron tensile test machine part way through extraction.

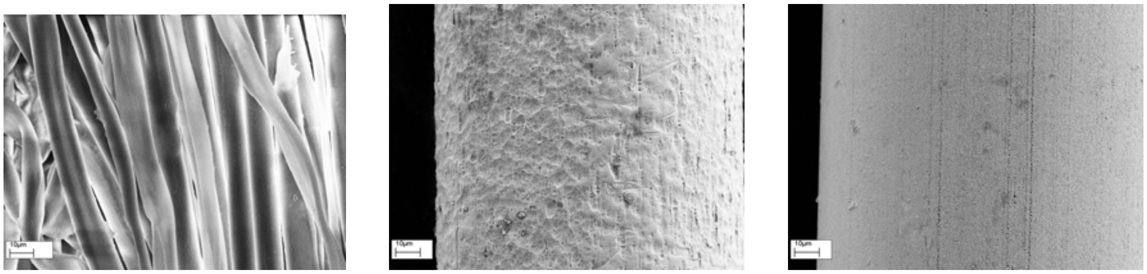
4 Results

4.1 Topographical evaluation of the components for extraction using a SEM system

SEM images were produce to provide an understanding of the surface properties of the NiTi wire being extracted (Fig. 7 image b.) shows the pitted surface of the 115µmØ NiTi wire that had been pickled after the final drawing down of the wire. This sample shows a marked difference to the smoother oxide finishes (Fig. 7 image c, d, e, f.) which discounting the post processing damage marks, show fine longitudinal striations formed during the drawing down of the wire. Comparing the topographical results the rougher pitted surface of the 115µmØ NiTi wire would suggest an increase in friction with the supporting structure but this could be at the expense of increased fibre damage after repeated movements. Further specific investigation of this relationship will be required to fully assess the influence the surface finish of the NiTi has on the supporting structure.

As a result of the finishes of the wires surface direct comparisons cannot be made between the 115µmØ NiTi wire and the other samples but have been included as a point of reference.

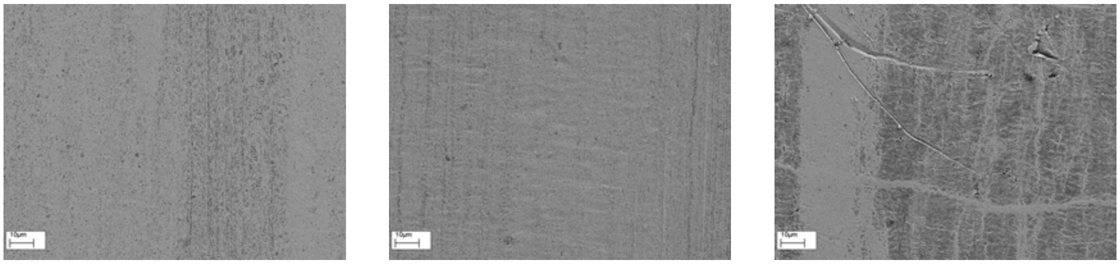
Fig. 7 SEM images of extracted components showing differences in topography (all scales are at 10µm)



a. Mercerised Cotton

b. 115µmØ NiTi wire pickled finish

c. 152µmØ wire oxide finish



d. 25x445µm wire oxide finish

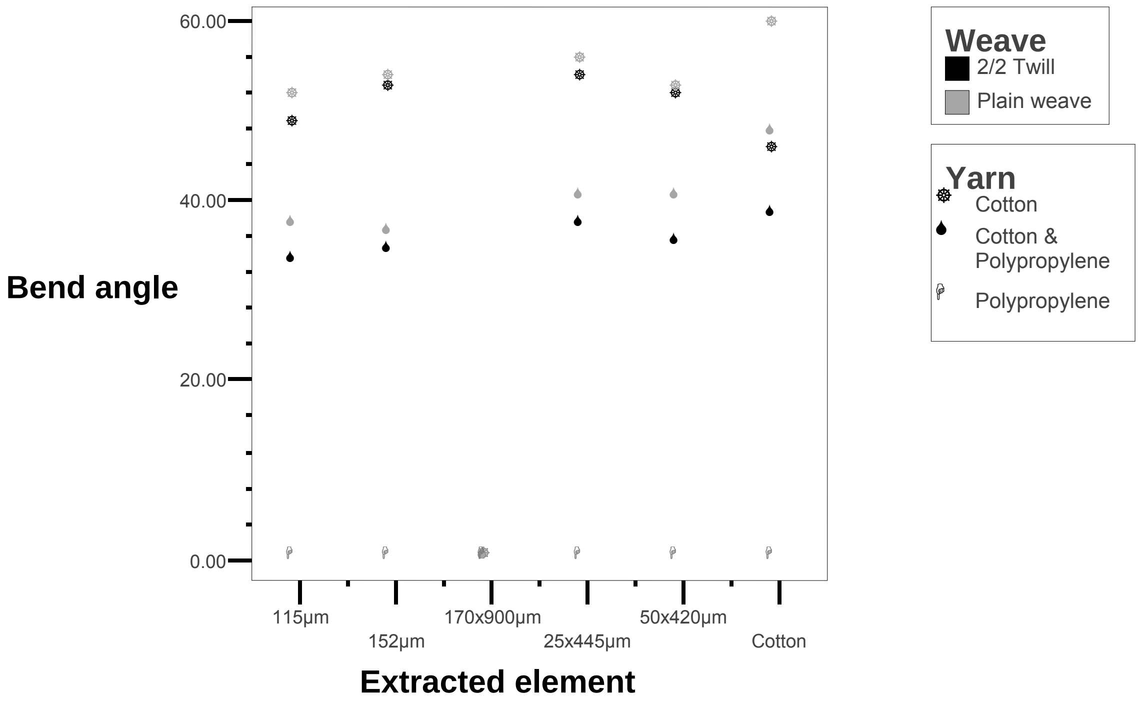
e. 50x420µm wire oxide finish

f. 170x900 wire oxide finish

4.2 Bend testing analysis

Initial analysis of the samples prior to testing determined that due to the stiffness of the 170x900µm wire and samples woven with a polypropylene warp and weft, bend testing would not be possible and readings of 0 were recorded. The results from the remaining samples (Fig. 8) demonstrate a clear trend with the plain weave sample demonstrating more flexibility with a higher bend angle. As predicted by the increased rigidity of the samples that used polypropylene in both the warp and weft the sample which consisted of a combined cotton and polypropylene warp demonstrated less flexibility to the cotton samples. Another point that was noted was the proportional difference between the results of the bend testing using the additional cotton warp yarn which demonstrated a greater divergence of the results than is seen in the NiTi sample. This would indicate that although noticeable differences were recorded between the weave structures the influence of the NiTi was reducing this effect.

Fig. 8 Effect of NiTi wire, yarn and weave have on the bend angle at 65mm extension



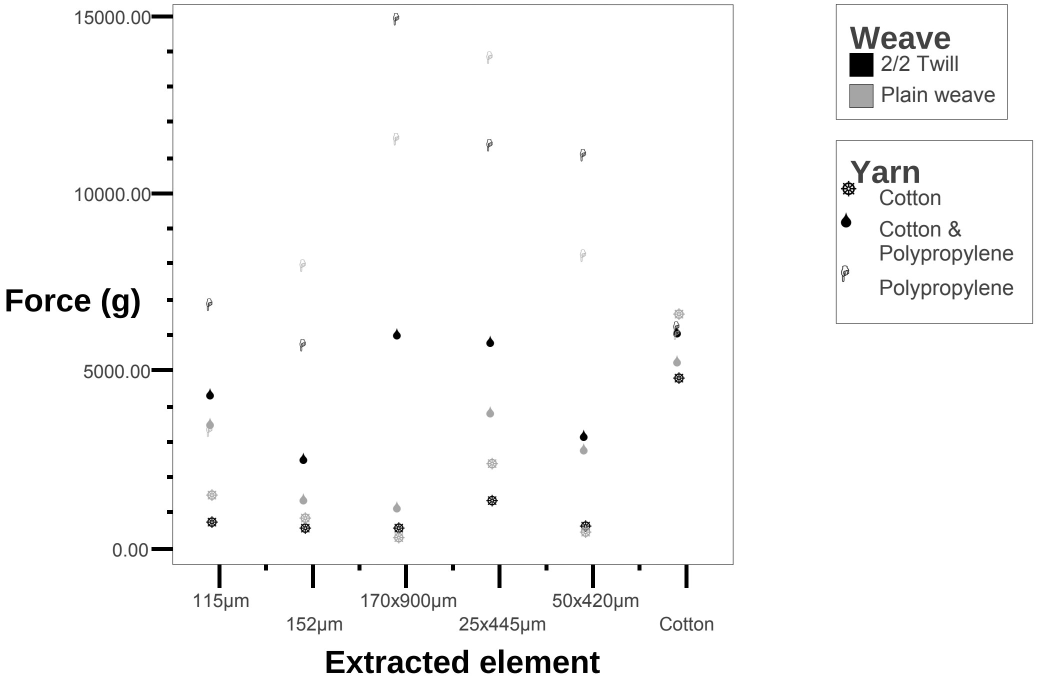
4.3 Extraction testing

A noticeable difference was established between the performances of samples using the three different supporting yarn combinations (Fig. 9). For the samples that used polypropylene in both the warp and the weft a markedly higher extraction forces was required across all the samples. This demonstrated a successful increase in friction and there for shape transfer when integrating NiTi into a woven polypropylene structure, but with a corresponding loss of flexibility which can be seen in the bend test analysis. It should be noted that in the polypropylene samples the reading for the extraction of the cotton yarn are in fact breaking strain readings as the yarn failed before extraction. Although the force required to extract the wire from the samples with the combined cotton and polypropylene warp was markedly less than the polypropylene samples, it was still notably higher than the cotton across all the samples.

The results investigating the effect the weave has on the inserted NiTi wire showed a general trend of an increase in force required to remove the NiTi from the 2/2 twill but with notable exceptions being the 25x445μm ribbon in the polypropylene sample and the 50x420μm 170x900μm NiTi in the cotton samples. The increased extraction forces required to remove the NiTi from the 2/2 twill sample that used polypropylene yarn in the warp could be a result of the increase number of polypropylene ends as a result of the sett of the fabric. Further investigation will be needed to clarify this

It was noted that the increased levels of force needed to extract the 25x445μm wire were due to the crimping of the wire within the woven structure. While this increase in friction between the NiTi and supporting structure is apparent when the NiTi wire is inactive if the wire is straightened during activation the loss of the crimp may result in the wire being removed more easily and will require further investigation.

Fig. 9 The results of extraction after manipulating the variables.



5 Discussion

The flexible and adaptable characteristics intrinsic to most textiles have throughout history made it the most suitable and widely used material to act as a second skin for protecting the human body especially for intimate apparel. This relationship is based on the textiles ability to interact with the human form. The ability to alter the materials properties by switching between a flexible, drapeable fabric with a traditional hand and a material that can take on a number of pre-programmed semi ridged forms is an important proposition for a number of industries including apparel, medical, aerospace and engineering.

Through tensile extraction tests, the ability to manipulate the dynamic friction between an inserted NiTi wires and woven structure has been demonstrated. The data collected has shown that this can be achieved by altering a number of independent variables such as yarn type, woven structure and NiTi profile. With the exception of the 170x900µm NiTi ribbon and samples woven using polypropylene in both the warp and weft, only minimal increases in stiffness were recorded in the bend tests, with results still comparable to the same sample types with an additional cotton yarn. The ability to independently manipulate variables such as yarn type and woven structure along the length of an inserted NiTi wire can produce both an increase and decrease in the transfer of force from the wire to the woven structure. This difference in force transfer is key to the creation of a secondary level of movement and control in active textile.

Proposed applications in the medical field could see the development of remotely controlled fastenings increasing the independence of the elderly and less mobile as well as in applications where dexterity is impaired as a result of restrictive safety wear. Adaptive and controllable garment could be developed for pressure dressings or for the stabilisation of weak or paralysed limbs, capable of both supporting and exercising limbs without the need for additional cumbersome mechanisms.

6 Conclusion and future research

This investigation represents a foundation for future research in the area of controllable textiles that use NiTi. It demonstrates the potential to manipulate the transfer of control from the NiTi wire to a woven structure on a number of levels while maintaining the properties of a fluidity textile. Further research is required to evaluate the specific effect of individual elements in more detail including:

- the effect the surface finish of the wire has on friction and subsequently the integrity of surrounding fibres after repeated cycles.
- the effect of an over sett polypropylene warp for plain weave compared to that of a 2/2 twill.
- the use of the crimping of a fine NiTi ribbon as a holding mechanism which is released on the activation of the NiTi.

There is also scope for the widening of the production parameters using jacquard weaves, for greater freedom of yarn placement and post production manipulation in the form of embroidery, laser-cutting and laser-etching.

The emerging field of active shape memory textiles should not be viewed in isolation but as an integral part of the wider range of materials that demonstrate forms of active shape control. The potential for the dynamic control of textiles has yet to be fully explored but will inevitably lead to new and innovative ways of utilising the specific attributes of woven textiles.

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