DYNAMIC CONTROL OF ACTIVE TEXTILES:

THE INTEGRATION OF NICKEL-TITANIUM SHAPE MEMORY ALLOYS AND THE MANIPULATION OF WOVEN STRUCTURES

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Abstract

The integration of wire-form, nickel titanium (NiTi), shape memory alloys (SMA), within woven structures, offers the potential to generate unique properties in this bi-material composite. The combination of two materials, one of which can be modified with regard 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. To date, there has been limited research into the impact textile structures could have on both direct and indirect shape transfer from an integrated SMA component.

This thesis overviews the integration of shape memory materials in textile structures informed through practice. In combination with a variety of natural and synthetic yarns, the investigation has examined how the manipulation of simple woven structures can be used to alter the direct and indirect mechanical shape transfer characteristics of from integrated NiTi components. In particular this thesis examines the influence of cloth sett, woven structure, and choice of yarn in combination with a variety of NiTi wire and ribbon. Composite samples were woven and the mechanical relationship with the integrated NiTi was investigated through a series of bend and tensile tests using mechanical mass loading and resultant extraction. The samples were validated by computer controlled tensile / compression testing machines. Subjective evaluations of visual and tactile properties were also conducted, together with comparative topography and morphology investigations using scanning electron microscopy.

The results of this research have been catalogued forming an extensive technical database, searchable by single or multiple design variables. This database is a valuable resource that will support future decision making within this emerging design field.

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Definitions

Anisotropic: Having different physical properties in different directions.

Austenite: High temperature parent phase of material.

Aromatic fibre: Organic compound which demonstrates high molecular stability (examples referred to in this thesis are polyester and Kevlar).

Count: Numerical value indicating the size of a yarn, indicating the relationship between length and weight.

Dent: Space between two adjacent wires in the reed used to space the warp ends.

Draft: Order in which warp ends are treaded through the correct heddle on the respective shaft.

End: Single warp thread.

Float: Unbound yarn in a woven fabric which extends over two or more adjacent ends or picks.

Inhomogeneous: Not uniform in composition.

Hand: Describes tactile qualities of a fabric perceived by touching, squeezing, or rubbing it.

Handle: See hand.

Hysteresis: The temperature difference between the point when the material is 50% transformed to an Austenite upon heating and 50% transformed to Martensite on cooling.

Isotropic: Having the same physical properties in all directions.

Martensite: Low temperature phase of material.

Pick: Single inserted weft yarn.

Programmed wire: An SMA or SMP component which has been processed to impart a given and returnable form.

Reed: A comb like device on a loom used to space the warp threads and beat down the weft threads.

Sett: Number of warp ends per unit and dispersal in the reed.

Smart materials: A smart structure is a non-biological physical structure having the following attributes:

i. a definite purpose
ii. means and imperative to achieve that purpose
iii. a biological pattern of function

(Spillman, Sirkis et al. 1996)

Trained wire: See Programmed wire.

Warp threads: Also known as ‘ends’.

Weft threads: Also known as ‘picks’ or ‘filling’.

The available reeds were measured in ends per inch rather than ends per cm. Because of this, the warp ends have all been calculated as a number of warp ends per inch (epi). When conversion is required, and in the database, the ratio 1 inch : 2.54 cm is used.

Throughout the thesis italic font is used to indicate words that are being used in a specialist context, for example, *smart* and *active* textiles.

Abbreviations

2/2T 2/2 Twill

A_f Austenite finish

A_s Austenite start

C Combined (e.g. CPW2/2T is a combined woven structure using plain weave surrounding the NiTi wire and 2/2 twill for the main body of the fabric)

Dc Double cloth (e.g. 2/2TDc is a double cloth fabric where the two faces are woven in 2/2 twill)

epcm Ends per centimetre

epd Ends per dent

epi Ends per inch

M_d Highest temperature to strain induced Martensite

M_f Martensite finish

M_s Martensite start

NiTi Nickel titanium (in the context of this thesis NiTi is used specifically to describe nickel titanium shape memory alloys)

P1 Phase 1 of investigation

P2 Phase 2 of investigation

P3 Phase 3 of investigation

PW Plain weave

PEF Peak extraction force

PET Polyester

PP Polypropylene

SE Superelastic

SMA Shape memory alloys

SME Shape memory effect

SMM Shape memory material

SMP Shape memory polymers

SW Satin Weave (6 end satin was used)

s Sample (e.g. s43)

S Selvedge (e.g. 2/2TPWS is a 2/2 twill fabric with a plain weave selvedge)

Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed

Date

Dedicated to my supportive loved ones.

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1 Introduction

This chapter summarises key elements contained within the thesis, introducing the research questions and including an overview of the background, justification for the investigation, methodology, outline of the thesis and the delimitations of the study.

1.1 Background to this research

The increasing development of materials and structures for specific applications has both driven and been driven by the requirements of a growing diversity of applications. This rapid development of application and material has led to the evolution of new high performance materials and structures that are often referred to as *engineered* or *smart*. The drive for the development of new materials has resulted in an increase in interdisciplinary investigation and the hybridisation of materials, structures and processes. The development of fibre based composites is one such area that is being increasingly utilised in advanced engineering and performance applications, stimulating collaborations that are both design and technology driven. Comparable to the multi-functional hierarchical fibre structures that dominate biology (Jeronimidis 2008), the inherent properties of textiles are ideally placed to provide frameworks into which additional levels of function can be integrated within a single cohesive structure. This biomimetic approach to design promotes an efficiency of materials and streamlining of design, embracing principles of sustainability and influencing developments across many disciplines and applications.

An area of materials development that has been investigated by a number of different disciplines, including textiles design, is that of shape memory materials (SMM), of which nickel titanium (NiTi) shape memory alloy (SMA) is one form. SMM and single component actuators have been developed that are capable of being integrated directly into textile structures with minimal compromise to the handle of the resulting cloth. Once integrated, these components have the potential to actively create macroscopic changes to the flexibility, structure, form or surface of the textile. Although the creation of actively controllable quasi-static and flexible structures could greatly alter the perception and use of materials, to date, there has been limited research into many aspects of the design and construction of these composite structures.

Depending on the technology available and end use, a number of different techniques have been employed for the attachment or integration of NiTi components to textile structures. Embroidery techniques have been used in grafted cardiovascular stents (Anson Medical 2009), a shirt with self rolling sleeves (Corpo Nove 2008) and a dress capable of altering its own hemline (Berzowska and Coelho 2005). Berzowska has also investigated the integration of NiTi wires into felted structures for the production of self-adapting brooches.

Research on the integration of NiTi wires into woven structures has concentrated predominantly on the development of relatively rigid composite structures for vibration dampening, impact resistance and the ability to withstand lightning strikes (Boussu, Bailleul et al. 2002; Boussu 2006; Foreman, Nensi et al. 2007). The area of NiTi integration into flexible woven structures has been less widely explored but with notable research coming from Chan (2004; 2007). Chan's investigations also explored the spinning of NiTi composite, fancy yarns and the use of flexible NiTi composite textiles for interiors where the aesthetic properties can be maximised. 'Oricalco' NiTi shape memory fabric by Grado Zero Espace (2009) was used in a shirt developed by the Italian fashion house Corpo Nove (Corpo Nove 2008) which can be *ironed* with warm air from, for example, a domestic hair dryer, to facilitate shape recovery.

Although research has investigated some aspects relating to the integration of NiTi into textiles, particularly woven structures, the available literature is still limited and application focused. As a result of this a focused study into the interfacial relationship of NiTi and supporting structures has so far not been undertaken. A particular aspect of this relationship is the understanding of the differences between direct and indirect shape transfer from the NiTi component to the supporting structure, and whether this can be utilised to facilitate or impede the creation of different patterns of movement along a single uniformly trained NiTi component.

1.2 Research questions

The questions addressed in this research are:

- How can the impact on the weavability and handle, resulting from the integration of NiTi shape memory components, be accommodated?
- How can the influence of specific design variables, including woven structure, cloth sett and choice of yarn, be used to alter the freedom of movement of integrated NiTi wires and ribbons and subsequently, direct and indirect mechanical shape transfer?

This thesis builds on the interdisciplinary foundations of shape memory composite textiles through a thorough evaluation and understanding of the incorporation and subsequent interfacial relationship between textiles and integrated NiTi components. It is concluded that controlled patterns of direct and indirect mechanical shape transfer can be created and manipulated along the length of a uniformly trained NiTi component, producing both direct and indirect shape transfers, resulting in the creation of dynamic control in woven structures.

1.3 Justification for research

The justification for and validity of this research is based on the development of a new class of flexible, active composites, which can be dynamically controlled in a pre-determined manner or in response to a changing environment. Although development into successful applications is currently limited, the setting out of a range of design parameters will help to highlight and stimulate new areas of investigation. This research will also play a future role in the emerging area of actively controlled shape memory polymers (SMP), discussed further in section 2.2. At present the use of SMP is limited in this area, but as their properties are developed and improved, many of the design principles relating to the effects the woven structures have on integrated NiTi components can be transferred to SMP.

The original focus of this thesis had been to investigate the manipulation of woven structures and surfaces using internally activated, controlled patterns of movement, with specific emphasis on the development of integrated, re-usable NiTi SMA fastenings in flexible woven structures. The direct integration of fastenings within flexible structures would result in the reduced visual impact and physical distortion of the fabric, due to the removal of additional components. Through the resistive heating of the NiTi, the subsequent possibility for the fastenings to be remotely controlled would open up applications, in areas such as protective clothing and apparel for the elderly, infirm or physically impaired, where manual dexterity is restricted. Although research into NiTi fastenings has evolved in the area of expansive or compressive mechanisms in rigid structures, there is no available literature regarding the development of integrated, actively controlled NiTi fastenings in flexible woven structures. On closer investigation of the available literature it was discovered that there was a general lack of research investigating the development of textile structures incorporating NiTi components, specifically the complex dynamic relationships between those components and flexible woven structure. The literature that does exist is primarily concerned with the integration or use of rigid composite structures (Foreman, Nensi et al. 2007) or applications where aesthetics were the primary concern (Chan Vili 2004; Berzowska and Coelho 2005). Although some valuable information could be gleaned from these sources there was limited discussion or data on how the basic components or structural properties either facilitated or impeded the movement of the integrated NiTi. The resulting lack of a clear foundation and the need to rely on the adoption of a number of assumptions and assertions in fundamental areas meant the research could quickly lose its integrity and therefore subsequent validity. As a result, the considered decision was made that a more valid and valuable contribution to the existing body of knowledge would be to take a step back and consider in more depth, the specific relationship between flexible woven structures and integrated NiTi components.

Key aspects that place and define this research within the current body of knowledge:

Current research position: Construction methods and parameters have been investigated for the integration of NiTi wires into woven structures (Boussu, Bailleul et al. 2002; Chan Vili 2004; Foreman, Nensi et al. 2007; Grado Zero Espace 2009), although data is limited due to the focus on specific applications.

Research response: A focused evaluation of an investigation into the optimisation of the dynamic interfacial relationship between integrated NiTi wires and flexible woven textile structures.

Current research position: Preparatory studies have been conducted by Chan (2004; 2007) on the different patterns of movement attainable by manipulating the woven structure and sett of the cloth.

Research response: An Investigation into the distinction between *direct* and *secondary* patterns of movement and the ability to create dynamic, repeatable patterns of movement across a woven structure and along a single NiTi component.

Current research position: Because the available literature is application focused the field of rigid fibre based and woven structures has remained separate to the integration of NiTi components into flexible woven structures.

Research response: An exploration of correlations between the rigidity of woven samples and the interfacial relationship between an inserted NiTi component and woven structures.

1.4 Methodology

The structure of this research originated from a very broad investigation into key areas relating to flexible materials, active *smart* materials and patterns of articulation and control. Chapter three initially focuses on and describes the selection of variables relating to the active materials, woven structures and test methods used to answer the research questions. To successfully and rigorously investigate the stated aims a combination of methodological approaches were employed. These drew on established methods of investigation used in the fields of materials, engineering and textiles. This combination was required to fully understand the interfacial relationship between the inserted NiTi component and woven structure to produce dynamic control in active textiles.

The initial investigation carried out in phase 1 of the research identifies the variables that would affect the interfacial relationship of a NiTi component integrated into a woven structure. This evaluation was based on an objective, theoretical review of the available literature in conjunction with prior knowledge of the properties and variables of woven structures.

The samples tested in phases 2 and 3 were produced within rigorously controlled parameters to maximise the comparability of each sample set. Subjective evaluations were carried out using haptic and visual methods, including comparative topography and morphology investigations using a scanning electron microscopy system (SEM). Investigations regarding the composition of the shape memory alloy were also conducted at the same time as the SEM imaging, using energy dispersive X-ray (EDX) analysis. The mechanical properties of composite samples were investigated using objective, quantitative methods which employed a series of bend and tensile tests. These were conducted using a flexometer for bend testing and mechanical mass loading for evaluation of static friction and extraction of the NiTi component from woven structures. The extraction testing was supplemented by an evaluation of dynamic friction using a computer controlled tensile / compression testing machine.

The presentation of results and research outcomes takes two forms. The main evaluation of the empirical research is presented in chapter four and consists of a systematic review of the variables tested, with key results expressed in graphical and text form, then evaluated and discussed, drawing conclusions from each phase of the investigation. In addition, a comprehensive database is submitted in two formats, which will serve as a resource for future investigation in this area. The first format is a PDF file, simply consisting of the sample data sheets showing all aspects of the individual sample production and testing, including images of samples. A second file is also submitted as a Filemaker Pro database, which has a lower ease of access due to the need to have a copy of Filemaker software. However, once accessed, it provides the same sample sheets as a fully searchable resource where individual fields, and combinations of fields, can be easily sorted for further evaluation and study.

1.5 Outline of thesis

Divided into five chapters and four appendices, figures 1 and 2 outline the progression and structure of the thesis through chapters one to two and three to five respectively. Chapter one introduces and summarises key aspects of the research, introduces the research questions and positions the work within the current body of knowledge. Chapter two (literature review) expands on the background to the research, reviewing the extent of the current literature and building the foundation on which the research is based. Within the literature review two key research issues are identified that place the study in the existing body of knowledge and formulate a response to the research questions. The first section reviews the interdisciplinary aspects of the investigation, with an overview of the field of material science and engineering, and links, through a biomimetic design approach, to developments within the fields of textiles and sustainability. The second research area covered in chapter two is the systematic refinement of the field of shape memory materials and their integration into textile structures. This starts with an overview of key material types and the mechanisms and levels of functionality in shape memory materials. Following a comparative discussion of SMA and SMP, the remainder of the chapter is concerned with specific factors in the development and potential of NiTi, including properties, mechanisms and applications, active NiTi composites, and finally literature relating to the development of active textile structures integrated with NiTi components.

Chapter three forms phase 1 of the investigation, addressing the first research aim with a systematic evaluation of variable factors relating to the selection of materials and methods to be used in phases 2 and 3, which make up the empirical evaluations of the thesis. Progressing through an assessment of textile structures, specific variables relating to woven fabrics, including weave and yarn types, and the setting theories of woven fabrics, NiTi properties are also discussed and selected. The final part of this chapter relates to the selection and description of production processing and testing methods that will be used in phases 2 and 3.

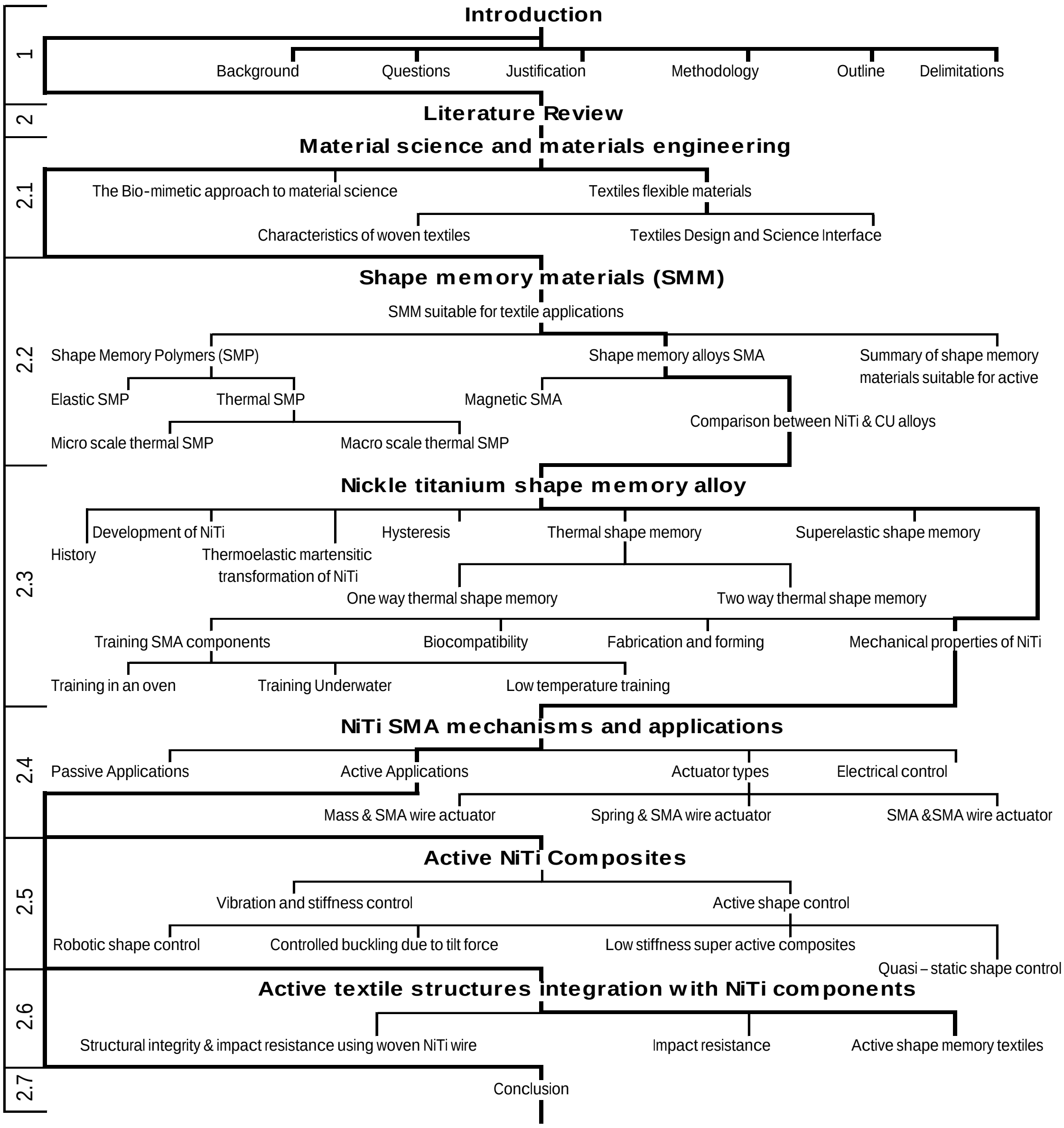


Figure 1 Structure and progression of the thesis through chapters one and two.

Chapter four is divided into six sections between two phases of enquiry, each containing three studies, detailing the aims, methods, samples produced and results of the empirical investigation.

Chapter five summarises the findings in answer to the research questions set out in section 1.2 and establishes the distinct contribution to knowledge outlined in section 1.3. In addition to concluding the current investigation chapter five also discusses the need for future research and proposes areas for the development of dynamically controlled active textiles.

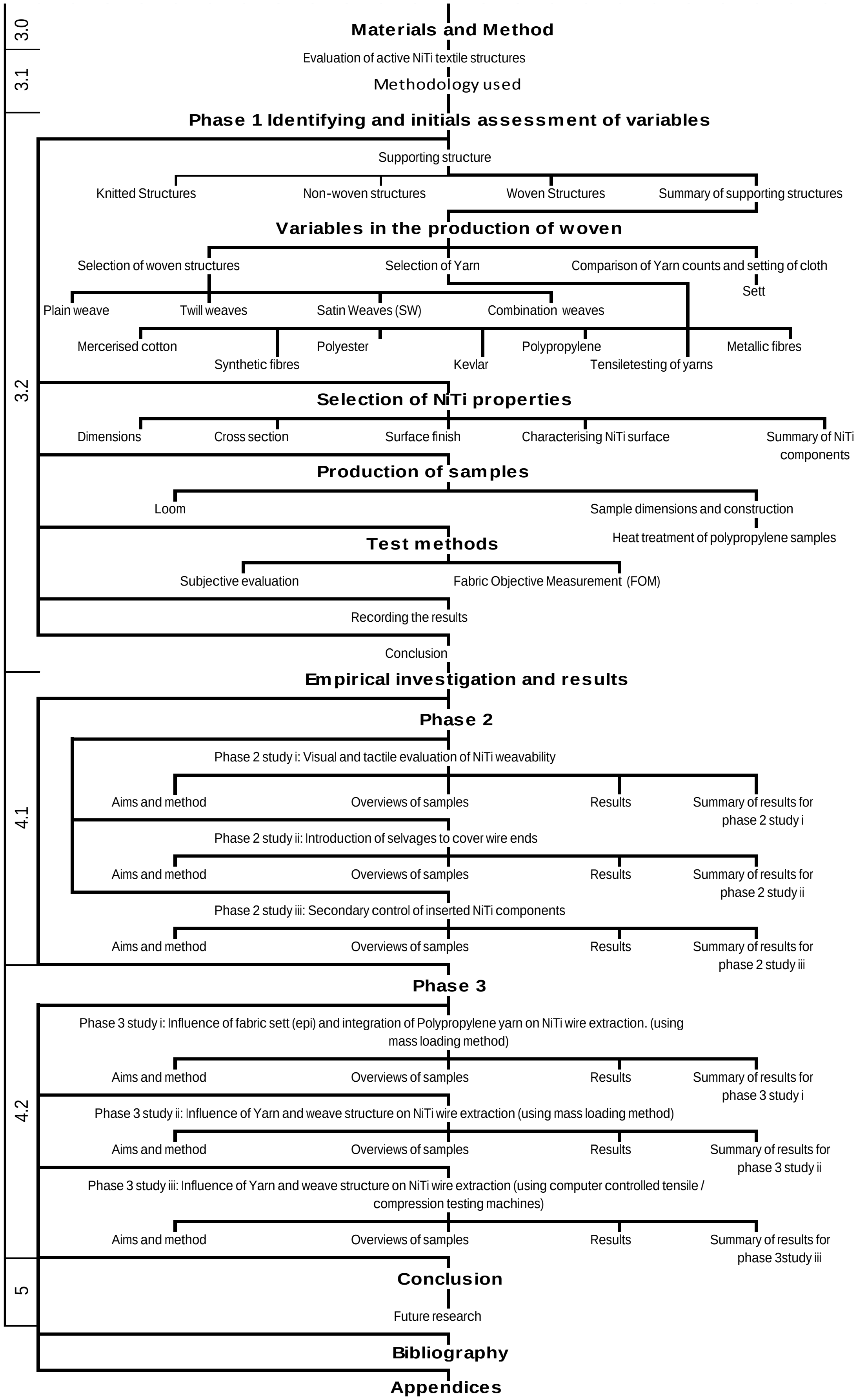


Figure 2 Structure and progression of the thesis through chapters three to five.

Appendices B and E are attached at the end of the thesis. Appendices A, C and D are available from the author (p.dyer@brighton.ac.uk) and provide fuller accounts of the sample variables, including a searchable database for both sample properties and results.

1.6 Delimitations of the research

Although a number of variables will be investigated, these are in specific relationship to the defined aims of the research and research questions (appendix A.). The empirical study is solely concerned with the design and development of flexible woven structures capable of incorporating a single component NiTi wire or ribbon. With respect to this limitation the development of knitted, and non woven structures, the use of multi component or fancy yarns incorporating NiTi, or the use of copper based SMA or SMP, are not pursued beyond the theoretical stages of the thesis. These limitations provide a strong focus for the research and the optimal combination of material and structure, given the present level of material development and process currently available.

This research is clearly in advance of the development of specific applications. The potential of the research is discussed including its suitability for future application; however, the development of specific applications, has not been pursued in this investigation.

2 Literature review

Placing this research within the wider related context of design, engineering and materials development, this chapter explores the interdisciplinary nature of composite shape memory textiles and the relationship between textiles and biomimetic design. Starting with a brief discussion on materials development, including the specific properties associated with textiles, the focus then shifts to the area of shape memory materials, and specifically the capabilities of NiTi shape memory alloys to provide active shape control from within a textile structure.

2.1 Material science and materials engineering

The field of material science is interdisciplinary, drawing on the knowledge of science, engineering and design to improve or manipulate existing materials and to develop and or discover new phenomena or materials through an understanding of their composition. With an increased knowledge and understanding of how materials function, many scientists now believe that the gap between technology and nature is closing (Forbes 2006) and has spawned a resurgence of interest in design inspired by nature and biomimetics. In recent years, another factor in the increasing interest in biomimetic design is the growing concern about sustainability. Designers have historically used natural structures as inspiration for form, but are now learning from and mimicking their efficient use of energy and material in their construction, with a focus on multi-functionality and adaptability.

2.1.1 The Biomimetic approach to material science

Natural structures are the result of millions of years of evolution and optimisation, becoming masters of efficiency, precision self repair and durability (Srinivasan and Mcfarlan 2001). Two main characteristics have been identified that are common to many natural structures: these are multi-functionality and hierarchical organisation. The combination of these two characteristics is the integration of different functions at different levels within one cohesive structure.

Investigations into biological design have shown that the functional element of many natural structures and mechanisms is engineered on a very small scale. Although we understand biological design on many levels, the question that researchers face is whether these can be developed to work on a human scale. Forbes (2006) warns designers, scientists and engineers that “A too zealous copying of nature is not advised. Bio-inspiration requires that the principles be abstracted from nature.”

The idea of ‘mimicking’ rather than trying to directly copy nature has been used in the development of fibre structures and reinforcements, developing the principles of natural biological structures into man-made non-biological materials. As our knowledge and technology increase, we are able to investigate and manipulate materials on smaller scales, from macrostructures (> 1000nm) to microstructures (100 to 1000 nm) and more recently, nanostructures (1 to 100nm) (Askeland and P.Phulé 2003). The ability to examine materials more closely has developed a greater understanding of biological mechanisms. We are better placed to develop materials that have a superior performance and to fulfil specific tasks or applications (Srinivasan and Mcfarlan 2001). An example of this can be seen in the complex hierarchical nature of tendons and corded yarn (Figure 3). Although yarn and rope have been spun or braided for thousands of years the understanding of these smaller structures has resulted in refinements and superior performance in the range of products available.

[redacted]

Figure 3 Comparison of hierarchical structure of a tendon and corded yarn (Srinivasan and Mcfarlan 2001).

The use of fibres is intrinsic to many aspects of biological design with 95% of biological structures having an underlying dependence on fibres of one sort or another (Jeronimidis 2008). In natural materials, variances within, between and across fibre layers, result in complex anisotropic structures that have superior strength to mass ratios, as well as demonstrating increased structural stability, flexibility and durability, when compared to many man-made materials that tend to be isotropic.

Exceptions to the isotropic structures of man-made materials are woven and knitted textiles that are similar to many biological materials in that they are composed of complex hierarchical fibre structures that can utilise the properties of many different fibre types seamlessly in a single material (Figure 4). In the textile industries, expertise in the design, production and handling of these complex structures already exists, making it ideally placed to play a central role in the development of this evolving area of material science. Like natural fibre structures, man-made textile structures can be used for the integration of specific properties or function at the point they are required, promoting the design concept of sustainability by maximizing properties and function whilst making efficiencies in materials and energy. Working in this manner has led to an interest in biomimetic design, investigating the similarities between the anisotropic hierarchical structures found in nature and those inherent in textiles. These properties can be enhanced by varying a number of parameters across the woven structure, including the sett of the fabric, weave type, yarn and finishing. These parameters can be further expanded using jacquard weaves for greater freedom of yarn placement and 3D woven structures for additional dimensionality to create complex structures where different properties can be inserted at an increased number of levels and stages of construction.

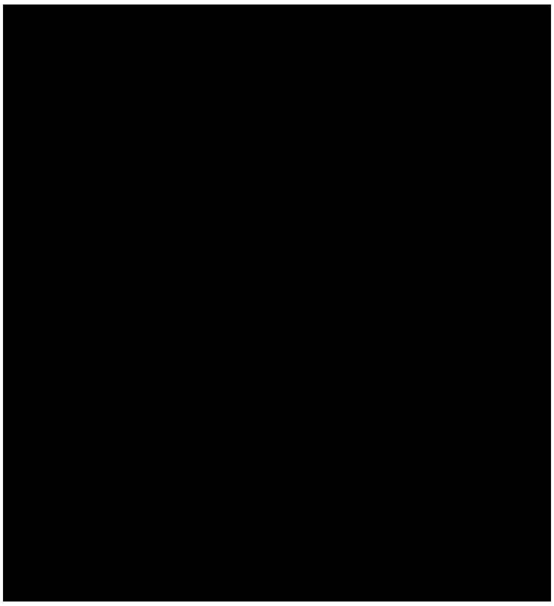


Figure 4 Carbon fibre and Kevlar fabric (McQuaid 2005). (Original in colour).

2.1.2 Textiles: flexible materials

Through a process of refinement and design over more than 8,000 years (Harris 2006) from the earliest rough woven material, textiles are now used in a diverse range of applications, including fine polyester micro-filament fabrics with a very soft ‘handle’, Carbon and Kevlar reinforced composite sails combining strength and lightness and $2m^3$ polypropylene cargo sacks capable of lifting 2,000 kg (McQuaid 2005). With the development of new fibres and technologies, textiles have spread into a vast number of everyday and specialised applications, often out-performing the materials that have conventionally been used for the task.

2.1.2.1 Characteristics and development of woven textiles

Unlike most materials that are more or less dimensionally stable, the unique engineering properties of textiles result in materials that behave neither as a true solid nor a liquid (Stylios 2005). In the introduction to ‘Structure and mechanics of Woven Fabric’, Hu (2004) discusses the properties and considerable differences between textiles and conventional engineering materials, describing them as:

- Inhomogeneous
- Lacking continuity
- Highly anisotropic
- Easily deformable

- Having the ability in normal use to suffer large strains and displacements, even under low stress
- Non linear and plastic at low stresses and under normal use and temperature ranges
- Able to form shapes with double curvature without buckling or forming sharp corners

It is these physical properties that from an engineering perspective make textiles highly complex and beneficial materials that are able to adapt and move in sympathy with the form to which they are attached. These unique properties are the result of textile production methods. The starting point at the fibre stage orders fine fibres or continuous filament into more or less aligned bundles, which then, using varying amounts of twist and tension, are spun into a yarn or thread, thereby increasing its strength. The directional lattice interlacements of individual fibres in the warp and weft of a textile cause the yarn to crimp and form spaces that allow movement and adaptation of form, as well as giving linear strength to the textile. Changing the number of interlacements in one repeat of the woven structure and so altering the crimp and size of the spaces would change a plain weave to a satin weave. The plain weave fabric demonstrates a low tensile stiffness and high 'in plain' shear stiffness when compared to a satin weave fabric that registers higher tensile stiffness and lower 'in plain' shear stiffness (Potluri and Jetavat 2006). These differences in performance can be utilised in the construction of a fabric that requires specific attributes in different areas that work independently as well as influencing the behaviour of the material as a whole.

When applied to composites, woven materials also exhibit many advantages over those using unidirectional materials, including:

- Improved structural integrity
- Resistance to cracking
- They are highly formable (drape) over complex shapes

The same properties, however, that make textiles useful and adaptive materials also result in difficulties for automation of handling and manufacture. This is still labour intensive, and therefore keeps production costs high (Hu 2004).

2.1.2.2 Development of the textiles design and science interface

The transfer of technologies, ideas and methods between textile design and science, has resulted in the realization of new design concepts and the opening up of fields (Gale and Kaur 2002). The integration of technology into textiles has often resulted in the attachment of what is usually *hard* technology onto a *soft*, flexible textile structure. A key aspect of the successful integration of technology is its suitability, from a functional perspective as well as a visual and haptic viewpoint, therefore ensuring that resulting products are not simply "Glorifying garments as gimmicky gadgets" (Stylios and Luo 2003). This approach appreciates more fully the complex interrelationship of fibre, yarn and structure, and the potential benefits these offer for development across disciplines.

2.2 Shape memory materials (SMM)

The shape memory effect is demonstrated by materials in many different ways from the small high frequency movements seen in piezoelectric materials to shape memory polymers which although the recovery is comparatively slow can recover completely from strains of 700% to 900%. This section investigates the main material types that demonstrate the shape memory effect and their suitability for integration into woven structures and the creation of active shape memory textiles. The evaluation of the SMM is based on the stimuli required to initiate the shape change, the impact the integrated component will have on the handle of the resulting textile and its ability to produce controlled patterns of movement on a macro scale. Focusing on shape memory polymers and alloys the benefits and disadvantages of these two material types are discussed in further detail.

2.2.1 Shape memory materials (SMM) suitable for textile applications

Shape memory materials are stimuli responsive, demonstrating an ability to change from a deformed shape to a pre-programmed shape as a result of being exposed to an external stimulus (Honkala 2006). The shape memory effect is most usually activated by a change in temperature, but for some, it can be induced by stress, magnetic or electrical fields, pH levels, UV light and, in some cases, water. This change is not simply a form of thermal expansion but is a reversible diffusionless transformation between two crystal microstructures which is thermally or stress induced.

Developments in SMM fall into four main material types:

- Shape Memory Alloys (SMA)
    - Magnetic Shape Memory Alloys
- Shape Memory Polymers (SMP)
    - Shape Memory Gels
- Piezoelectric materials
- Natural shape memory materials

In an overview of active materials Kumar and Lagoudas (2008) isolate two variables that are key for the successful development of the ideal active material. The first of the variables is the actuation energy density which denotes the available work output per unit volume and is obtained from the actuation strain and stress (Figure 5). The second is the actuation frequency which is plotted against the energy density in Figure 6. Maximisation of the potential for an active actuation material requires both a high energy density as well as high frequency. Figure 5 and Figure 6 analyse these two variables in relation to a number of currently available active materials.

[redacted]

Figure 5 Actuation energy density diagram indicating typical ranges of actuation, stress and strain (Kumar and Lagoudas 2008).

[redacted]

Figure 6 Actuation frequency diagram for a range of active materials (Kumar and Lagoudas 2008).

Although the actuation frequency of SMA is in the lower half of the selected materials (Figure 6), Figure 5 shows that SMA are capable of shape recovery even under high loads. This ability to effect a useable shape change even while under loading makes them suitable for integration into composite structures to create controlled patterns of movement.

Shape memory alloys and polymers have both been developed into fine mono filaments or wires and thin films offering physical and functional properties on a macroscopic scale that can be integrated and utilised to produce active, controlled patterns of movement in flexible materials. The wide range of properties and potential to be either superelastically or thermally activated, mean SMA and SMP can be utilized in many applications to control or sense changes in materials, such as shape, position, strain, stiffness, natural frequency, dampening, friction, and vapour penetration. Although SMA and SMP can demonstrate similar shape memory characteristics the mechanisms of the shape change are very different. In SMP, the shape change is as a result of the glass transition; in SMA the shape change properties are a result of a transformation between Martensite and Austenite phases: both of these characteristics will be discussed later in sections 2.2.2.2 and 2.3.3. When exposed to a stimulus SMA demonstrate the potential to provide force, whereas SMP provide mechanical property loss (Hu and Mondal 2006). These differences can be utilised within structures to perform complementary tasks.

Piezoelectric materials

Piezoelectric materials expand when an electrical field is applied and conversely generate an electrical charge when pressure is applied. Piezoelectric materials are capable of very high cyclic speeds but offer very small units of expansion for a given length. For these reasons coupled with the brittle nature of the material piezoelectric materials are unsuitable for direct integration into textile structures and the production of controlled patterns of movement across a fabric. Possible exceptions to the brittle nature of piezoelectric materials may be polymer based Piezo effect materials such as Polyvinylidene fluoride (PVDF) (Zhang, Bharti et al. 2002) that demonstrate flexibility and can be produced in relatively small cross-section forms. Also thin-film deposition of Piezo materials, directly deposited onto yarn or bulk textiles (Haccart, Cattan et al. 2002), could potentially modify the dynamic performance of these textiles.

Natural shape memory materials

The shape memory effect can be viewed in many natural materials and in particular a number of fibres that are already widely used in the textile industry. Examples are cotton, which swells in high humidity (Stylios 2006), and a similar reaction which can be seen as a result of the thermal and hydrothermal properties of wool fibres (Hu 2008). Although these materials demonstrate a physical change, it is of a very small order of magnitude and is unable to offer a high level functionality.

2.2.2 Shape Memory Polymers

Although at present shape memory polymers are not able to demonstrate the same shape change capabilities as SMA, as new polymers are developed they will play an increasingly important role. Interest in the development of thermally activated SMP was first seen in Japan in 1984 (Honkala 2006) and an extensive review of the area has recently been conducted by Hu (2007). SMP are capable of sensing and reacting to an external stimulus, resulting in a change from a temporary deformed shape back to a pre-set shape. They can be triggered by a variety of different stimuli, including stress, heat, light, electric field, magnetic field, chemical, moisture and pH levels (Hu and Mondal 2006; Hu 2007). The shape memory effect seen in polymers is not the result of the specific properties of a single material but rather a result of a combination of polymers with different morphologies and processing (Lendlein and Kelch 2002). At present, polymers that react to heat and stress, demonstrate the most useful characteristics for the production of integrated active control on a macro level (Honkala 2006).

2.2.2.1 Elastic shape memory polymers

Elastic recovery, following the application of tension, compression, torsion or bending of materials, can also be described as a ‘memory’ effect. Shape memory polymers that demonstrate elastic shape memory have been successfully integrated into the textile industry and are in everyday use in many items of clothing in the form of natural rubber and elastain (commonly called Spandex in the US). Rubber is a natural shape memory polymer that at room temperature demonstrates elastic properties. After the discovery of vulcanization in 1839, the development of cut rubber threads was established and was in commercial production by 1850 (Irie 1999). In the 1930s the technique of producing extruded rubber filaments was perfected and the manufacture of very fine, round filaments was achieved (Cook 2005). Rubber is able to achieve 100% recovery from elongations under stress of between 700 – 900%; on removal of the stress, it reverts immediately to its original length. Developed in 1959 by Joseph Shivers, a chemist at DuPont, elastain was sold under the brand name Lycra, which has since become synonymous across the world with all forms of elastic fibre. Elastain is spun from a complex block copolymer that exploits the combination of the high crystallinety and hardness of polyurethane segments (not less than 85%), and yet remains ‘rubbery’ due to alternating segments of polyethylene glycol. Elastain can repetitively recover from elongations of 300 – 700% without breaking and although rubber has a lower rate of stress decay, elastain is stronger and more durable (Taylor 1990).

2.2.2.2 Thermal shape memory polymers

Thermal SMP are stable in at least two separate phases associated with separate temperatures. At the lower temperature phase the material is able to be deformed and hold a temporary shape. On reaching the glass transition temperature (*T*g), the cross-links release, allowing the material to revert from the deformed shape to the trained shape. The higher temperature phase holds the material at a trained shape T*perm,* above which the material melts and can be formed using conventional techniques (Lendlein and Kelch 2002). Thermal SMP have been developed independently at two distinct scales, able to produce either macro or micro responses to temperature change.

2.2.2.3 Micro scale thermal shape memory polymers

Diaplex, developed by Mitsubishi Heavy Industries is an example of a polymer material that demonstrates active thermal shape memory on a micro scale. Diaplex was originally developed as a membrane for the textile market that could be bonded to supporting fabrics. Research conducted by Stylios (2007) has led to the development of a process capable of drawing and spinning a fibre of Diaplex that subsequently can be woven or knitted into a fabric, offering greater flexibility and scope for three dimensional production and the integration of other fibres to further enhance performance. Diaplex is able to sense and react to the combination of internal and external garment conditions. It achieves this by its ability, when warmed, to open pores in its membrane to release water vapour from inside the garment whilst retaining its waterproof quality, due to the fineness of its pores. If conditions cool, the pores in the film contract, sealing in the wearer's body heat until it rises again. The ability to selectively and autonomously adapt its microstructure and regulate the environmental conditions within the garment closely mimics the natural ability of our skin. The ability to mimic the skin's response to temperature change within a textile is an important development in the area of breathable, all weather fabrics, suitable for active wear. The design and development requirements of materials suitable for active wear are demanding and often include that the fabric to be waterproof, breathable, warm, wind proof, durable, flexible, elastic and soft to the touch (Hu 2004).

2.2.2.4 Macro scale thermal shape memory polymers

As well as the straight elastic effect, natural rubber can also demonstrate a form of thermal shape memory, although its functional use is limited. When held under stress and cooled to below its glass transition temperature Tg of around -196°C, rubber will lose its elasticity and retain the deformed shape until the temperature is raised above its Tg (Irie 1999). Recent developments of macro scale shape memory polymers have focused on electrochemical artificial muscles such as poly-electrolyte gels, ionic polymer gels and electro-activated polymers (EAP).

The development of shape memory polymers that are active on a macro scale is still at an early stage of investigation and the literature for understanding the functional properties is limited (Hu and Mondal 2006; Hu 2007). It is predicted though, that applications for SMP textiles will be both extensive and diverse, encompassing areas such as healthcare and telemedicine; military, police and other emergency services; sport and leisure; entertainment; and fashion wear (Hu 2007). An early success in the medical arena has been the production of the self-tying suture by MnemoScience (2001). This suturing material is capable of tying the perfect knot during surgery, in areas where access is limited or obstructed. Activated a few degrees above body temperature the suture transforms to its permanent shape contracting and thus tightening the knot.

Chan's investigation into the design of smart textiles based on shape memory materials (Chan Vili and Stylios 2003; Stylios 2006; Chan Vili 2007) included the production of spun SMP composite fancy yarns, which were subsequently woven into a range of cloths using a variety of structures. Similar studies have also been carried out using knitted structures (Winchester and Stylios 2003).

When seen as a potential material for integration into a textile structure, shape memory polymers have many benefits over metallic materials such as shape memory alloys (Honkala 2006).
The benefits are:

- The ability to recover from deformations of 300% to 400% compared to 8% for SMA.

- SMP can be programmed into the parent shape at 65°C; SMA requires programming at 400-500°C, which is beyond the tolerances of most traditional fibres.
- The recovery temperature of SMP is easier to control than that of SMA.
- The integration of polymer fibres is already well established in the textile industry.
- SMP can be coloured as part of standard textile dyeing processes.
- The material cost of SMP is less than that of SMA.

An initial limiting factor with SMP was its inability to carry an electrical current and it could not therefore be resistively heated. This meant that it was reliant on changes to the surrounding temperature from an external heat source, which prevented selective activation of individual components. In 2004, a team from Konkuk University, Korea, produced the first conductive SMP, adding carbon nano-tubes to conventional polyurethane SMP. The conductivity of this first fibre was poor due to the uneven dispersion of the carbon nano-tubes. In later research Paik and his team (2006) greatly increased the conductive performance, developing a new method of fabrication known as in situ polymerization.

In the available literature, a large number of potential applications are cited, covering almost all aspects of our daily lives, as well as industrial components. Despite the interest shown in the potential for the material, the commercial development of shape memory polymers has been limited. One of the most likely reasons for this lack of commercial development are the very low recovery forces and recovery times, restricting its potential in commercial applications (Honkala 2006). When compared to SMA, SMP perform poorly in these fundamental areas, having a recovery force of about 1/100th that of SMA and reaction times of between 25 and 60 seconds when compared to fractions of a second for SMA.

2.2.3 Shape memory alloys

Shape memory alloys like shape memory polymers demonstrate an ability to change from a deformed shape to a pre-programmed shape as a result of being exposed to an external stimulus. Whereas in SMP this is due to a glass transformation, in SMA, such as Nickel Titanium (NiTi), it is as a result of the alloy 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. The phase transformation is inherent in the alloy and is the basic mechanism for its unique shape memory properties occurring as a result of heating or cooling, or the application or removal of stress.

2.2.3.1 Magnetic shape memory alloys

Discovered in 1996 by Ullakko and his team, magnetic shape memory alloys have received a lot of interest in recent years. Magnetic shape memory alloys are capable of maintaining high frequency transformations with large strokes and force for extended periods of time without significant degradation or fatigue (Honkala 2006). The utilisation of these properties, combined with the ability to withstand strains of 10% and the removal of the need for heating for activation, make them a viable option for integration into textile structures. The limitation on this at present is the complex control mechanisms required for repeatable activation of isolated wires in flexible materials and the need for magnetic fields to be active around the body.

2.2.3.2 Comparison between NiTi and Cu based alloys

The majority of developments and commercial exploitation of SMA has focused on two basic alloy types, Nickel Titanium and a number of copper based alloys including CuZnAl, CuAlNi CuZnSi, and CuZnSn (Hodgson, Wu et al. c2004). Table 1 compares the economic, physical and shape memory properties of NiTi and Cu based alloys which would play a part in any decision concerning their suitability for use in specific tasks.

NiTi alloy has many characteristics that set it apart from other SMA and in spite of the higher cost of the materials and production they are by far the most popular SMA used in commercial applications (Honkala 2006; Stylios 2006). When it comes to design decisions it is often the superior properties and functionality of NiTi, such as recovery force, cyclic performance, maximum strain recovery, durability and bio compatibility, that outweigh the financial savings a Cu alloy would offer. Material led design can often be seen in specialist areas such as medical applications that utilise NiTi's specific properties, resulting in the properties themselves stimulating the design process rather than a material being chosen to fulfil a task (Honkala 2006).

	NiTi alloys	Cu based alloys
Economic		
Raw materials (Tadaki 1999; Honkala 2006)	High	Relatively inexpensive
Composition control, melting and casting (Humbeeck and Stalmans 1999; Tadaki 1999; Honkala 2006)	High: requiring to be melted in a vacuum in repeated steps. Composition critical	Relatively inexpensive: can be melted and extruded in air. Composition critical
Forming, rolling and extrusion (Humbeeck and Stalmans 1999)	Hot - difficult – Very difficult	Warm – easy – fairly easy
Cold working (Humbeeck and Stalmans 1999)	Fair - difficult	Restricted
Machinability (Humbeeck and Stalmans 1999)	Difficult - bad	Very good - easy
Physical		
Melting point (Humbeeck and Stalmans 1999)	1240 – 1310 °C	950 – 1050 °C
Density (Humbeeck and Stalmans 1999) NiTi only (Hodgson, Wu et al. c2004)	6.45 g/cm³	7.2 – 8 g/cm³ (depending on alloy)
Ultimate tensile strength (Humbeeck and Stalmans 1999; Tadaki 1999)	800 – 1500 MPa	400 – 900 MPa
Electrical conductivity (Tadaki 1999; Honkala 2006)	Relatively high resistance	Low resistance
Thermal conductivity (Tadaki 1999)		Good
Thermal stability and ageing (Honkala 2006)	Good	
Corrosion performance (Humbeeck and Stalmans 1999; Tadaki 1999)	Excellent Similar to 300 series Stainless steel and comparable to pure titanium	Good – poor Similar to aluminium bronzes
Biological compatibility (Humbeeck and Stalmans 1999)	Excellent	Bad
Shape memory		
Transformation temperature range (Hodgson, Wu et al. c2004)	-180 - +100°C	-180 - +200°C (depending on alloy)
Transformation Hysteresis (Hodgson, Wu et al. c2004)	30 °C	4 – 35 °C (depending on alloy)
Recovery strain (Humbeeck and Stalmans 1999; Honkala 2006)	8.5%	2.5% – 6% (depending on alloy)
Max recovery stress (Humbeeck and Stalmans 1999)	500 – 900 MPa	400 – 700 MPa
Work output (Humbeeck and Stalmans 1999)	1 – 4 J/g	1 J/g
Max temp. held for 1 hour (Humbeeck and Stalmans 1999)	400 °C	160 – 300 °C (depending on alloy)
Superelastic energy storage (Humbeeck and Stalmans 1999)	6.5 J/g	1.8 J/g

Table 1 Comparison of selected properties for NiTi and Cu based alloys. Values have been selected from a more extensive list of comparable properties (Salmans 1996).

2.2.4 Summary of shape memory materials suitable for active textiles

After investigating the varied material types that demonstrate the shape memory effect SMA and SMP offer the most potential for the development of dynamic patterns of control in active textiles. Although SMP offer many advantages when considering suitable SMM for integration as effective actuators in active textile structures their limited response times and recovery forces limit their use at the present time. The superior mechanical and shape memory properties of SMA over SMP mean that they are more able to perform the tasks and with the production of fine wires and ribbons there is limited impact on the overall handle of the resulting textile.

For this research NiTi SMA were chosen over Cu based alloys and shape memory polymers. In spite of the increased costs of material, NiTi SMA offer superior mechanical properties, corrosion resistance and biocompatibility. The latter of these is particularly important when considering materials which will be used in close proximity to the human body.

2.3 Nickel Titanium shape memory alloy

This section investigates in more detail the history and development of NiTi SMA's physical and mechanical properties as well as their processing requirements. The evaluation of these variables offers an initial insight into the, possibilities and opportunities this bi-phasic material has to offer the development of dynamically controlled active textiles.

2.3.1 History

The first reported reference to the shape memory effect (SME) in a metal was observed in an alloy of gold-cadmium (AuCd) in 1932 by Swedish physicist Arne Ölander (Otsuka and Wayman 1999). If the AuCd alloy is deformed soon after reaching a full Martensite structure it will demonstrate a plastic SME. However if the alloy is allowed to age in its Martensitic state for more than 14 hours before it is deformed it was discovered that it demonstrates rubber-like, pseudo elastic properties similar to superelasticity. Following this discovery, in 1938 Greninger and Mooradian observed the formation and disappearance of a Martensitic phase in brass (CuZn). This controlled phase transformation was stimulated by increasing and decreasing the alloy's temperature (Honkala 2006). The breakthrough, though, in the development of a commercially viable SMA came in 1962 when Buehler and his co-workers at the Naval Ordinance Laboratory in the United States discovered the shape memory effect in an atomically equivalent alloy of Nickel - Titanium (NiTi). (Hodgson, Wu et al. c2004). The shape memory effect has since been seen in a number of different alloys demonstrating a wide range of properties, transformation temperatures and hysteresis (Table 2).

Alloy	Composition	Transformation Temperature Range		Transformation Hysteresis (approx.)	
		deg.C	deg.F	deg.C	deg.F
Ag-Cd	44/49 at.% Cd	-190 to -50	-310 to -60	15	25
Au-Cd	46.5/50 at.% Cd	30 to 100	85 to 212	15	25
Cu-Al-Ni	**14/14.5 wt.% Al 3/4.5 wt.% Ni**	**-140 to 100**	**-220 to 212**	**35**	**65**
Cu-Sn	approx. 15 at.% Sn	-120 to 30	-185 to 85		
Cu-Zn	38.5/41.5 wt.% Zn	-180 to -10	-290 to 15	10	20
Cu-Zn-X (X = Si,Sn,Al)	**a few wt.% of X**	**-180 to 200**	**-290 to 390**	**10**	**20**
In-Ti	18/23 at.% Ti	60 to 100	140 to 212	4	7
Ni-Al	36/38 at.% Al	-180 to 100	-290 to 212	10	20
Ni-Ti	**49/51 at.% Ni**	**-50 to 110**	**-60 to 230**	**30**	**55**
Fe-Pt	approx. 25 at.% Pt	approx.-130	approx.-200	4	7
Mn-Cu	5/35 at.% Cu	-250 to 180	-420 to 355	25	45
Fe-Mn-Si	32 wt.% Mn, 6 wt.% Si	-200 to 150	-330 to 300	100	180

Table 2 Examples of shape memory alloys including composition, transformation temperature and hysteresis (Hodgson, Wu et al. c2004).

2.3.2 Development of NiTi

The shape memory effect was first observed in Nickel Titanium Alloys in 1962 by Buehler and co-workers at the United States Naval Ordnance Laboratory (Hodgson, Wu et al. c1990). In 1970 the first successful application of SMA was as a device for high pressure hydraulic tube coupling for the U.S. Navy's F-14 Fighter aircraft (Wu and Schetky 2000) known as Cryofit®. This method of coupling requires the use of an SMA cylinder that whilst in its low temperature Martensite form (cooled in liquid nitrogen) is placed over the tubes to be joined. After the coupling is in place the temperature is allowed to rise to the ambient temperature where it reaches Austenite; it expands to the programmed form and applies a constant pressure to the joint. Other connecting devices include connectors for electrical cabling and constraining rings for less demanding compression fastenings. In spite of intensive investigation after the initial success of the Cryofit® coupling, the next fifteen years saw NiTi fall into a technological push scenario, looking for a market which was able to afford it and to utilise its specific properties (Melton 1999). Niche areas that accommodated the high development costs for superior performance were the defence industry and medical applications. At this point defence interests concentrated on the development of secure electrical connectors and fasteners that were required for demanding roles. Efforts to use NiTi as an implant material, by Johnson and Alicandri in 1968, led to its first reported medical use in 1970 (Ryhänen 1999). In the early 1980s there was limited use in orthodontics as well as orthopaedics. The major breakthrough in medical applications came in the mid 1990s with the first widespread use of NiTi in stent design. With the trend in modern medicine for minimal invasive surgery the use of NiTi has flourished. As a result of NiTi's unique properties such as elastic / thermal deployment, biocompatibility, physiological compatibility, kink resistance, constancy of stress, fatigue resistance and MRI compatibility it has successfully been used in medical applications as diverse as vascular stents, vena cava filters, guide wires, retrieval baskets, bone staples, endoscopic and catheter instruments, as well as dental implants and eyeglass frames (Duerig, Pelton et al. 1996; Sreekumar, Nagarajan et al. 2007; Reade 2009).

2.3.3 Thermoelastic Martensitic transformation of NiTi

The thermoelastic Martensitic transformation seen in NiTi is a result of the bi-phasic transformation between two temperature dependent crystalline structures, known as Martensite and Austenite phases. The transformation between the phases occurs because the crystal lattice structures accommodate the lowest energy state at a given temperature (Otsuka and Wayman 1999). NiTi can demonstrate three distinct forms: Martensite, stress induced Martensite (superelasticity) and Austenite.

- Martensite is a phase that occurs when atoms in a solid material move co-operatively, often in a shear-like mechanism (Otsuka and Wayman 1999). Martensite has a rhombic structure and is a weaker low temperature phase that is soft, ductile and easily deformed without stress hardening.
- Full stress induced Martensite is a deformable state that occurs above the Austenite finish temperature (A_f) as a result of external stress. On release of the stress the material reverts immediately from stress induced Martensite to the programmed Austenite shape at A_f. This behaviour has a highly elastic (superelastic) rubber-like quality.
- Austenite is the parent phase and when heated to the Austenite finish temperature (A_f) all forms of Martensite revert back to the pre programmed form. Austenite is the high temperature phase and a cubic structure that is stronger, harder and less easily deformed than Martensite.

Thermal phase transformation is seen when the alloy is heated from the weaker, low temperature form, Martensite, or when cooled from the stronger, high temperature form, Austenite. Once programmed the alloy can be deformed while in Martensite, then returned to its programmed shape in Austenite (Figure 7 and Table 3). This transformation can be repeated for many cycles by heating to A_f followed by cooling to M_f. This is known as thermal shape memory. The application and removal of stress is known as superelastic shape memory (Ryhänen 1999). A wide range of transformation temperatures can be achieved with NiTi SMA, ranging from –50°C to 110°C by accurately altering the composition of the alloy (Hodgson, Wu et al. c2004). An additional, minor adjustment (+/- 10°C) to the thermodynamic profile can be achieved through heat treatment and processing.

[redacted]

Figure 7 Schematic of the phase transitions and crystal lattice structures during the shape memory effect (Honkala 2006).

Martensite finish temperature	M_f	Material fully transformed into the Martensite phase
Austenite start temperature	A_s	Point where the transformation from Martensite to Austenite starts
Austenite finish temperature	A_f	Material fully transformed into the Austenite phase
Martensite start temperature	M_s	Point where the transformation from Austenite to Martensite starts
Martensite d. temperature	M_d	Between A_f and M_d stress induced Martensite occurs (superelasticity). Above M_d plastic deformation occurs permanently.

Table 3 The five distinct points in the transitions between the two phases.

2.3.4 Hysteresis

When Martensitic NiTi is heated, the temperature at 50% transformation from Martensite to Austenite is higher than the corresponding temperature at 50% transformation from Austenite to Martensite. The temperature difference between these two transition points is known as hysteresis (H). In NiTi the hysteresis temperature range can be between 20°C and 30°C resulting in an alloy with an A_f of 65°C requiring cooling to < 45°C to revert to its full Martensite state M_f (Ryhänen 1999).

2.3.5 Thermal shape memory

Thermal shape memory can be seen in two different forms, one–way and two-way shape memory. To initiate both of these forms of thermal shape memory an external heat stimulus is required to raise the material to its transition temperature. The temperature rise can be achieved through the general ambient temperature, or selectively by passing an electric current through the material to resistively heat it to the transition temperature.

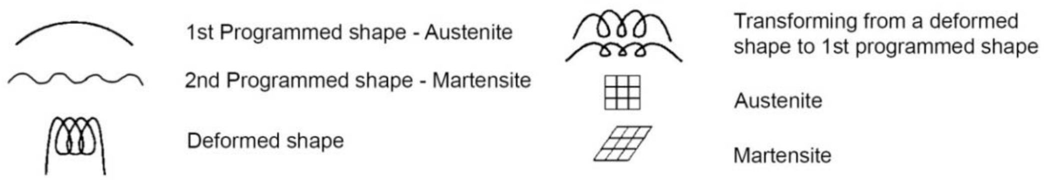


Figure 8 Key for Figure 9 to Figure 11.

2.3.5.1 One way thermal shape memory

One-way thermal shape memory is the phenomenon seen when a programmed NiTi alloy transforms from a deformed shape to a programmed shape due to heating (Figure 9). When Martensitic NiTi is heated above its Martensite start (M_s) temperature to its Martensite finish (M_f) temperature, it will start to transform into Austenite. The point at which this transition starts is known as the Austenite start temperature (A_s). When this transition is complete the NiTi will have reached its Austenite finish temperature and will take on the parent or programmed form. On cooling from Austenite the NiTi will start to transfer to M_s retaining the parent form until it reaches its M_f temperature. This deforming can be repeated over many thousands or millions of cycles. On reaching A_f the shape transformation occurs very swiftly and with considerable usable force that is capable of large displacements. It is the speed and strength of this shape change combined with the very soft, easily deformable Martensite phase, that has contributed to NiTi being the most commercially developed SMA.

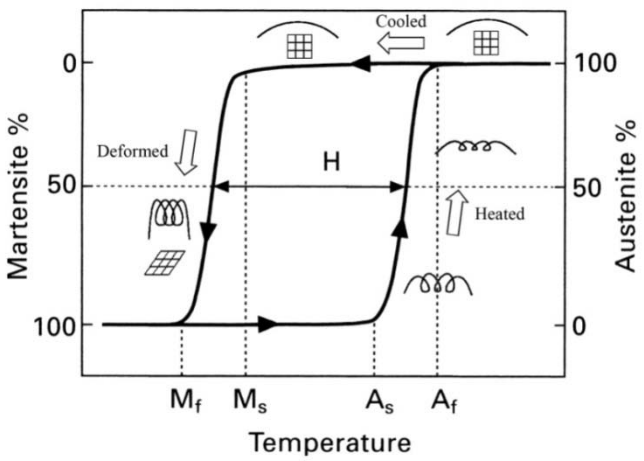


Figure 9 The transformation between the Martensite and Austenite phases in one way thermal shape memory alloy.

2.3.5.2 Two way thermal shape memory

Two way shape memory is achievable in certain conditions when, as well as the Austenite phase being programmed to a shape, the Martensite phase is also trained to remember a shape (Otsuka and Wayman 1999). The training of the Martensite phase to adopt a pre-determined shape is a complex one requiring many accurately repeated cycles of heating and stressing the alloy to the required shape. Once the alloy has been successfully trained it will behave in the same way as the one way thermal shape memory effect until it is cooled from A_f to M_f. At this point the two way shape memory alloy will adopt the second trained shape, shown in Figure 10. The use of the two-way SMA is limited and is often replaced by a bias spring or other return mechanism (Johnson Matthey c2008). The key reason for the limited use of the two-way SMA, is that compared to the recoverable strains of the one way thermal shape memory effect those of the two way effect are very low at only 2%, the transformation forces are very low and the memory can be easily removed with only slight overheating.

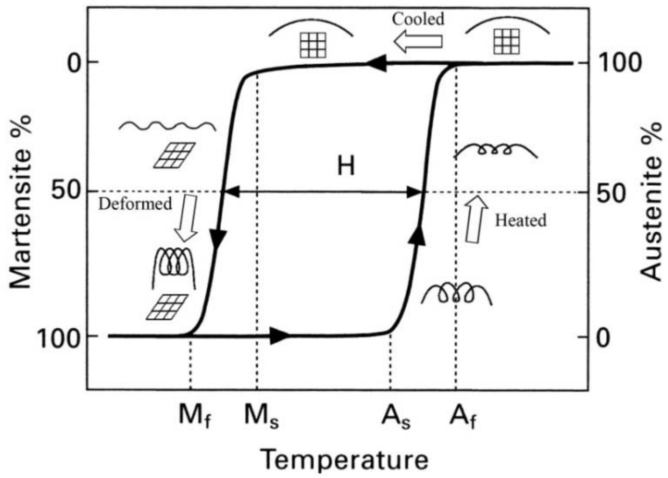


Figure 10 The transformation between the Martensite and Austenite phases in two way thermal shape memory alloys.

2.3.6 Superelastic shape memory

Superelastic NiTi demonstrates an elastic quality as its structure changes due to deformation stresses (twinned Martensite) and returns to the original geometry due to the un-twinning of Martensite on the removal of the stress. When the temperature of a normal SMA is raised above A_s it will stay in an Austenite form until the temperature is lowered to $M_{s.}$ In the case of alloys that exhibit superelastic qualities when the temperature is only slightly above A_s, the application of an external mechanical stress results in the alloy starting to exhibit a Martensitic transformation. This is known as stress induced Martensite (Honkala 2006). This transformation is the basis of superelastic behaviour in NiTi alloys. Between the A_s and A_f temperatures only a partial reverse transformation is seen; it is above the A_f temperature that full superelastic reverse transformation is achieved. When the external stress is applied the alloy immediately strains and the increasing strain results in constant stress behaviour. When the external mechanical stress is removed the alloy reverts immediately to the Austenite state and programmed shape (Figure 11). The transition back to Austenite from the stress induced Martensite is as a direct result of the removal of the external mechanical stress and does not require heating as is usually required in the transition from Martensite to Austenite (Hodgson, Wu et al. c2004). If the temperature up to which stress induced Martensite can occur (M_d) is exceeded, NiTi loses its shape memory ability and can be plastically deformed by slipping like conventional materials (Ryhänen 1999).

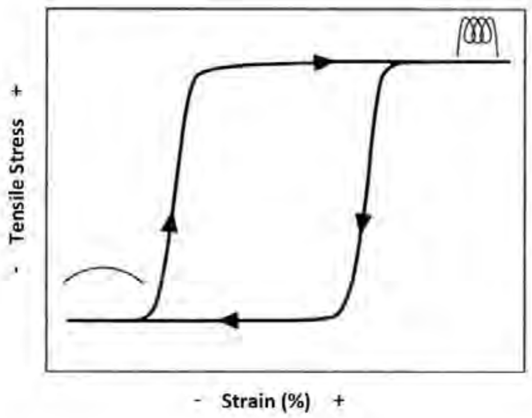


Figure 11 The transformation in superelastic shape memory alloy.

2.3.7 Mechanical properties of NiTi

The potential of the SME in NiTi is a product of the mechanical differences between the Martensite phase and Austenite phase (Table 4). The ability of NiTi SMA to alternate between two phases that have different yield strengths and Young's Moduli, result in an ability to transform small changes in one or more thermo mechanical variable (temperature, strain or external stress) to effect a larger useable change or return force (Humbeeck and Stalmans 1999). The mechanical properties of NiTi can be altered in a number of different ways including changes to its composition and through heat treatment and work hardening.

Property	Unit	Martensite	Austenite
Melting Temperature	°C	1310	
Density	g/cu.cm	6.45	
Resistivity	µΩ/cm	80	100
Thermal Conductivity	W/cm	9	18
Young's Modulus	GPa	23 – 41	70 - 80
Yield Strength	MPa	70 – 140	195 - 690
Ultimate Tensile Strength	MPa	895 fully annealed	
Ultimate Tensile Strength	MPa	1900 work hardened	
Transformation Temperature	°C	-200 - +110	
Latent Heat of Transformation	kJ/kg	167	
Max. Shape Memory Strain	%	8	

Table 4 Comparison of Martensite and Austenite properties of an equiatomic NiTi alloy with an A_f of 100 °C (Memory Metalle 2008).

The most usual proportions of alloying nickel – titanium to produce SMA is in atomically equal quantities (approximately 49% nickel by weight). Due to the alloy's moderate solubility other metallic elements can be added to modify both mechanical and transformation properties. The most usual addition is an increase in nickel content by up to 1% lowering the transformation temperature and increasing the yield strength of the Austenite. Other elements that have been alloyed with NiTi are Iron and chromium to also lower the transformation temperature and copper to decrease the hysteresis and deformation stress of Martensite (Hodgson, Wu et al. c2004). During heat treatment and processing minor adjustments to the thermodynamic profile can be achieved by altering the transition temperature +/- 10 ° C. Another result of precise heating and work hardening is a stronger Austenite phase and more malleable Martensite phase that produces a material demonstrating two way shape memory.

2.3.8 Fabrication and forming

The fabrication and production of NiTi alloy has to overcome a number of critical factors. Titanium is very reactive with oxygen, which will be discussed further in section 3.2.6.3, and must be processed in a vacuum (Wu 2001) or in an inert gas atmosphere. The most common methods used are vacuum induction melting and vacuum consumable arc melting. Other methods that are used on an experimental scale are electron beam melting, argon arc melting and plasma melting which are discussed further by Suzuki (1999). The composition of the alloy is critical with even minor changes substantially altering the transition temperature and mechanical properties of the alloy. The melt process is usually repeated several times after turning the ingot 180° to increase the homogeneity of the alloy and accuracy of the composition.

Once the final ingot is cleaned by removing the surface layer, it is forged and rolled into a bar or slab before further processing into cast components, or being drawn and rolled into wires, ribbon or sheet (Table 5). NiTi is easily worked at temperatures above 530°C with an optimum hot working temperature of 800°C. Cold working is increasingly difficult especially when the Ni content exceeds 51% as the alloy work hardens rapidly. In its annealed state NiTi has a yield strength of 100 MPa which is similar to annealed copper or aluminium. When cold-drawn the yield strength can increase to 1500 MPa. Drilling, milling or lathe turning is difficult and although grinding is not difficult, the abrasion loss of the grinding tool is high (Wu 2001). Other manufacturing techniques such as wire erosion, spark erosion, water-jet abrasive cutting and laser cutting have been employed for commercial manufacturing.

Cross section	Dimensions
Wire	25 µm - 5 mm Ø
Tube	125 µm - 6.4mm outer Ø Down to 50 µm wall thickness
Ribbon and Strip	50 x 25 μm^2 - 10.1 x 0.76mm^2
Sheet	From 20 µm thickness and 100mm width

Table 5 Common commercially produced cross sections and dimensions of NiTi (Memory Metalle 2008).

2.3.9 Biocompatibility

The medical applications and biocompatibility of NiTi has been well documented (Miyazaki 1999; Pelton, Stockel et al. 1999; Poncet 2000) and since the late 1970s it has played a major role in developments in medical science particularly with respect to minimal invasive surgery and the use of catheters and endoscopes (Shabalovskaya 1996). The biocompatibility of NiTi is both of interest and of importance when considering its integration into textile structures as many possible applications could necessitate close contact with the skin. There are also applications, such as stent design, that already combine NiTi with textiles and involve insertion into the body requiring in vivo biocompatibility with soft tissue as well as bone. Considering the two elements individually there is a contrast in the individual biological responses. Pure Ti is generally considered to be extremely well tolerated by soft tissue and bone showing neither toxic nor inflammatory responses (Ryhänen 1999). Ni is an essential trace element in vertebrates, including humans in a quantity close to 0.1 ppm (Trepanier and Pelton). In its pure state nickel is less reactive demonstrating resistance to many acids / alkalis as well as not readily oxidising. In spite of this, in contact with the skin and tissue nickel can be toxic, causing severe inflammation, necrosis of tissue and tumour growth in the tissue following skin contact or surrounding the implant site (Shabalovskaya, Anderegg et al. 2003).

The biocompatibility of NiTi is more complex than originally thought. On first inspection the surface was seen to be formed from a hard ceramic layer of TiO_2 with depleted Ni and as such delayed a systematic study of the NiTi surface. It has since been shown that depending on the surface treatment of the alloy either a Ti or Ni biased surface can be produced. Shabalovskaya discovered that when NiTi is mechanically polished, using a 600grit abrasive, surface finish, diffusion of Ni atoms to the surface was made easier through the channels and defects of the material (Shabalovskaya 2003). For this reason chemical polishing is often used to give a smoother more uniform finish, removing soluble particles and leaving only insoluble TiO_2 particles on the surface, thus reducing the migration of Ni atoms to the surface (Shabalovskaya, Rondelli et al. 2004). Ryhänen (1999) found that NiTi (45%Ni, 46%Ti) when compared to stainless steel AISI 316LVM and ASTM Grade 2 commercially pure titanium, an equal or superior biological, nearly inert, response was achieved.

2.3.10 Shape setting SMA components

The use of a NiTi shape memory or superelastic elements for a particular application generally requires the training of the NiTi to a custom shape. The process required to set the shape is similar whether beginning with NiTi in the form of wire, ribbon, strip, sheet, tubing, or bar. Shape setting (or *training*) is accomplished by constraining the NiTi element on a mandrel or jig of the desired shape and applying an appropriate heat treatment. The heat treatment methods used to set shapes in both shape memory and superelastic forms of NiTi are similar.

2.3.10.1 Conventional shape setting in an oven

The conventional method of training NiTi SMA components is in a high temperature oven. The heat treatment parameters chosen to set both the shape and the properties of the part are critical and usually fine tuning experimentally is needed to determine the desired requirements of each part. In general, temperatures as low as 400°C and times as short as 1-2 minutes can be used to set the shape, but generally a temperature closer to 500°C and longer periods of time are required. Although the desired NiTi shapes and properties are largely imparted by the time the components reach the selected maximum temperature, it is imperative that the time at the required temperature is met or components will not behave consistently or to the required level. For this reason larger components (e.g. bars and rods) or components using substantial constraining jigs, will require longer heating times to allow for the temperature of the part to equalise and reach the desired temperature. After heating the components are usually cooled via a water quench or, if both the parts and the fixture are small, rapid air cooling can be used. If a higher heat treatment time and temperature is used when training shape memory components an increase in the actuation temperature of the part is achieved in conjunction with a sharper thermal response. However, there is usually a concurrent drop either in peak force (for shape memory elements) or in plateau stresses (for superelastic elements). There is also an accompanying decrease in the ability of the NiTi element to resist permanent deformation.

2.3.10.2 Underwater and low temperature shape training

A method has been developed that facilitates the shape setting of textile-shape memory alloy composites (EU project Loose & Tight 2009). The common method employed to heat–treat NiTi alloys is unsuitable for use on textile composites due to the relatively high temperatures required, that would damage the supporting textile structure. The technique entails a rapid temperature rise, using electrical resistance heating in a ‘burst’ mode. Current is applied to the metal alloys for a 10-20 millisecond period, while the sample is immersed in a bath of de-ionised water. In this method the water acts as a heat-sink, protecting the more thermally sensitive textile structure from the temperatures required to train the NiTi.

Recently published information from the Pan European Hybrid Textile Project Avalon (Reade 2009) has discussed the development of a NiTi heat treatment technique that can be performed at below 200°C. Although information is limited given the patent pending status the development of a comparatively low heat setting procedure would greatly broaden the possible applications of NiTi textile composites.

2.4 NiTi SMA mechanisms and applications

Nickel titanium shape memory alloys (NiTi SMA) are often perceived as a material, capable of resolving many design problems when incorporated into a wide range of applications; the number of commercially successful applications, however, is very small (Melton 1999). Technical requirements and limits are often not fully understood and result in a mis-evaluation of the properties. This can result in a designer requiring a product that out performs the available materials. There are a number of criteria that restrict the use of NiTi in new applications. The foremost of these is cost. As NiTi is used more widely and the applications grow the cost decreases, but it still remains an expensive solution to problems that other alloys or mechanisms can effectively perform at reduced cost. For this reason the use of NiTi results in high cost specialist applications, where its specific properties, such as shape memory effect, biocompatibility or actuation with limited moving components can be utilised offering a unique solution capable of outperforming other alternative methods where the benefits out-weigh the additional cost.

The commercial applications that have reached the market are found in a varied and diverse range of industries (Table 6). From early applications, such as mobile phone antennae, devices for joining high pressure hydraulic lines in aircraft, joining / fastening applications and actuation tasks, as well as medical devices including orthodontic arch wires, guide-wires, vena-cava filters and cardio vascular stents, other industrial products have been commercialised that use the thermal and elastic properties of the metal to produce, domestic and automotive thermal control and protection devices (thermostats), and many others are at development stage.

Area of use or type of device	Application
Superelastic devices	
Medical	Vascular, Oesophageal and biliary stents Guide wires, pins and localisation hooks Flexible, steerable, hingeless surgical instruments Remote suturing and stapling devices Bone suture anchors
Dental	Endodontic root canal files Orthodontic arches
Other	Eyeglass frames Brassiere under wires Cellular telephone antennae Damping devices
Shape memory devices	
Medical	Pulmonary embolism filters, vascular stents
Couplings	Hydraulic and pneumatic Electrical zero insertion force connectors
Thermostatic regulators and switches	Kettles Liquid and gas regulator valves
Other	Robotics Satellite release bolts Aerospace actuators

Table 6 Superelastic and thermal shape memory alloy applications (Melton 1999; Miyazaki 1999; Ohkata and Suzuki 1999; Kumar and Lagoudas 2008; Reade 2009; Johnson Matthey c2004; Johnson Matthey c2008).

2.4.1 Passive applications

The majority of current commercial applications come under the umbrella of passive applications and predominantly make use of the superelastic shape memory effect in NiTi in a very simple way utilising it only once (Wijst 1998). In medical applications such as stents, the superelastic effect is utilised in deployment where the alloy's ability to recover from large deformations means that after being deformed and constrained in a catheter, the device elastically recovers and reverts to its programmed shape. Once deployed the stent is designed to exert even radial expansion to the wall of the vessel facilitating dilation. These same properties are also utilised in endoscopic instruments where strength needs to be coupled with flexibility and recovery of form (Duerig, Pelton et al. 1996). Other devices react as a simple on off controller, such as thermostatic valves (Ohkata and Suzuki 1999) (Figure 12) and safety switches that utilise the temperature of the surrounding fluid to drive the shape change.

[redacted]

Figure 12 Schematic of a thermal mixing water valve using a linear SMA spring (Ohkata and Suzuki 1999).

2.4.2 Active applications

Since the late 1980s, there has been increased interest in mechanisms incorporating SMA that have more than a simple on/off switching function (Boller 1999). Many applications have been proposed that utilise the active, sensing, dampening, shape control and actuation characteristics of SMA, including adaptive profile wings, hinge free solar panels and robotic arms. The development of the more sophisticated active mechanisms has been much slower to reach the commercial market than that of passive applications. Much of the research in active applications is still in the development phase focusing on proof of concept rather than the development of prototypes for commercial applications (Stalmans, Tsoi et al. 2000; Kumar and Lagoudas 2008; Reade 2009). The realisation of many of these applications has been slowed by the need to understand the behaviour and relationship of the SMA as a control input within and to the mechanism. Furthermore before commercial applications can be fully developed there are still production issues regarding the adaptation and integration of SMA in composite materials (Boller 1999). Another factor that has slowed the development of SMA integrated composite structures is the interdisciplinary knowledge required. Successful research has resulted from co-operation between research groups with sufficient expertise on SMAs, electronics and the supporting structure whether it is a polymer matrix or a textile (Stalmans, Michaud et al. 1998).

2.4.3 Actuator types

The design and development of active structures requires a return mechanism or bias force to deform the structure prior to the SMA being reactivated and returning to its programmed form. Most of the research into the active control of structures has focused on the integration of one way SMA, with two way SMA receiving less attention. Although two way SMA are able to return to a second programmed shape on cooling, the transformation to the second form is slower and releases a less useable force (Johnson Matthey c2008) which, if relied upon as the sole return, will slow cyclic speeds. Liang and Wijst (1991; 1998) identified three basic alternative mechanisms that could be used to act as a return for a one way shape memory wire: mass, spring / elastic and SMA.

2.4.3.1 Mass and SMA wire actuator

In its simplest form, this mechanism (Figure 13) consists of a mass suspended from a fixed point by a SMA wire. When the SMA is at M_f it is deformed, causing an extension, due to the mass-load. When the temperature of the SMA is increased to A_f the SMA is able to lift the weight and hold it for as long as the higher temperature phase is maintained. On cooling the SMA is once again deformed by the weight. The addition of a force transforms it from the simple one-operation mechanism seen in applications like the ‘Cryofit’ pipe couplings and opens up the possibility for the design of active, cyclic mechanisms. Depending on the application, the external force could simply be an additional mass, the influence of gravity, to induce stress needed to facilitate the deformation.

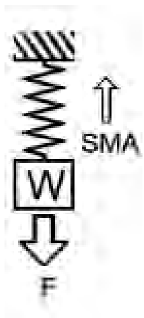


Figure 13 Schematic of a mass and SMA wire actuator.

2.4.3.2 Spring and SMA wire actuator

The spring and SMA wire actuator (Figure 14) is commonly seen in thermal protection valves that are controlled by an external stimulus, and can be used to regulate the temperature of liquids and gasses (Figure 12). In its basic form, the point where the spring and SMA meet is controlled by the changing influence and mechanical strength of the SMA wire. This mechanism utilises potential energy stored in the spring to deform the NiTi when the temperature is in the Martensite range, (Ms to M_f.). When the temperature is increased, causing a structural change, shown in the formation of Austenite (As-Af), SMA strain recovery occurs generating a force. This is essentially the same basic principle illustrated by the example of a mass suspended from an SMA wire actuator, but with the return force of the spring constantly acting on the SMA. The spring bias, compared to a mass bias, is a more adaptable and independent form of actuation, leading to less design constraint.

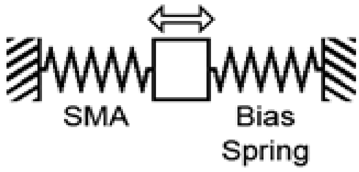


Figure 14 Spring and SMA wire actuator.

2.4.3.3 SMA and SMA wire actuator

The mechanism and behaviour of this actuator is in many ways a refinement of the spring and SMA wire actuator. Using two or more SMA wires, which can be independently heated to A_f, instead of a spring, adds greater control and timing to the mechanism. In the spring and SMA wire actuator the mechanism is always in a transition between on and off. In an actuator that uses two SMA wires four different characteristics can be independently selected, two different active and relaxed states, a state where both wires are relaxed and also a state where both wires are active (Figure 15). The combination of multiple SMA wires placed in parallel can be used to produce complex patterns of actuation as well as a method of increasing cyclic speeds. The use of electrical resistance heating of two opposed SMA wires, using pulsing techniques, adds another functional dimension to actuation techniques; controllable, proportional movement is possible giving good precision in the linear movement of each opposed wire (Anson 2004).

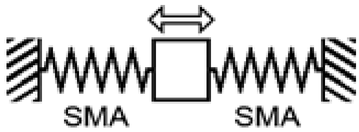


Figure 15 SMA and SMA wire actuator.

2.4.4 Electrical control

A common way of controlling the temperature of specific NiTi wires is by electrical resistive heating. NiTi can be resistively heated at low voltages resulting in large displacements or force. An example of this can be seen from a single 10cm, 150µmØ Flexinol wire, which with a power input of 0.8 watts produces a half second contraction that can lift 330g. This process can be repeated at a rate of 20 cycles a minute in still air at 20°C (Gilbertson 2000). Although the electrical properties of NiTi wires are well documented the electrical and subsequent mechanical behaviour of an SMA wire in a composite structure depends heavily on the temperature field in the matrix material as a result of resistively heating the SMA wire to activation (Wijst, Schreurs et al. 1997).

Wang's investigation (2008) into the encapsulation of NiTi wires into composite structures describes how thin composite structures require less energy to activate as the effects of shear and compression forces are minimal. In addition a NiTi wire integrated into a thinner structure will be less influenced by the composition of the composite and the generation of a thermal mass as a result of increased cyclic speeds and extended periods of activation. Wang noted that when comparing the activation times of NiTi wires in air and submerged in water, due to the increased energy dispersion in water the activation times were slower yet the cooling times were quicker. The effect the supporting structure plays can be seen in Wang's comparison of similar latex and silicone samples actuated with electrical pulses of the same value. The results showed that larger bend angle could be achieved in the latex samples for two reasons:

- The elastic modulus and thickness was greater in the silicone samples.
- The thermal conductivity of silicone is better than that of rubber latex.

Other factors that affect the overall performance of resistively heated SMA wires are the voltage and duration of electrical pulse. It was found that at low voltage, even for long power-on times, the bend angle of a wire trained to an arc remained small. Conversely even with short pulses of higher voltage large bend angles can be obtained although the corresponding return times were longer.

2.5 Active NiTi composites

Coverage in the available literature of developments into actively controlled textile structures that utilise integrated NiTi SMA wires, has been limited. Due to the limitations of the available literature on NiTi shape memory textiles, this research has also investigated the broader area SMA embedded in hard and flexible composites as well as free un-encapsulated constructions seen in many robotic mechanisms. Although not directly related to textile structures, parallels with the more documented fields of rigid composites (Foreman, Nensi et al. 2007), flexible beams (Stalmans, Michaud et al. 1998; Parlinska, Clech et al. 2000), adaptive aerodynamic skins (Mani, Lagoudas et al. 2008; Simpson and Boller 2008), biomimetic muscle structures (Kim, Kim et al. 2005; Wang, Hang et al. 2008), active catheters (Veeramani, Buckner et al. 2008), and the design of small robotic devices (Wijst 1998; Elahinia and Ahmadian 2006; Price, Jnifene et al. 2007; Sreekumar, Nagarajan et al. 2007), have been used to inform this emerging area of design research. In the majority of these models the SMA wire is directly attached to, or embedded in, the supporting structure, resulting in a constant interfacial relationship between the wire and supporting structure until failure. When inserted into the anisotropic structure of a textile, the composite offers the opportunity to develop complex adaptive structures that are controlled on a number of different levels. Research into the development of applications that utilise the active properties of NiTi SMA have focused on four main aspects of control relating to different scales of movement and are illustrated in Table 7.

Whether embedded within or attached to a structure, the basis for each of these aspects of control is similar in nature. In stiffness control the aim is to control shape change and stabilize and preserve the integrity of the original structure. In shape control the reverse is required and the aim is to alter the material's geometry from its original form to improve performance or to perform a specific function (Choi and Lee 1998).

<table>
<tr><th></th><th>Mode of integration</th><th>Aspects / scale active control is utilised</th><th>Function of control</th></tr>
<tr><td>Vibration control</td><td rowspan="2">Hard / rigid material often an epoxy resin matrix often reinforced with uni-directional carbon, glass or Kevlar fibre</td><td rowspan="2">Small changes within an often hard material</td><td>Control and dampening of vibrations or change the resonance frequency of the material</td></tr>
<tr><td>Stiffness / buckling control</td><td>Stabilize the integrity of the structural form, preventing buckling and failure</td></tr>
<tr><td>Direct active shape control</td><td>Soft / flexible material, often silicone, other polymer matrix or textile structure</td><td>Larger movement to effect a change in the shape or configuration of the material, whilst still keeping the movement within the material's structure</td><td>Control and manipulation of flexible skins and components for both functional and aesthetic applications</td></tr>
<tr><td>Secondary shape control (Robotic tendons)</td><td>External (un-encapsulated), usually anchored between two points</td><td>Often magnifying small movements via an additional mechanism</td><td>Used like tendons to actuate components, linear and rotary</td></tr>
</table>

Table 7 Scales and forms of active control using SMA components.

The mechanical behaviour of composites is heavily dependent on the thermal and physical properties of the supporting matrix. In traditional composite skins the SMA wire is held in place by a combination of supporting fibres and epoxy resin or alternatively in a silicone matrix. When encapsulated in an epoxy or silicone matrix the cyclic behaviour of the SMA is very much influenced by the matrix.

2.5.1 Vibration and stiffness control

The development of composite structures with integrated SMA wire actuators has largely focused on active vibration and stiffness control (Chaudhry and Rogers 1991). The reduction and control of vibrations and subsequent maintenance of the rigidity of a structure plays a fundamental part in preserving its integrity and stability. The lighter and more flexible constructions that are now being developed are more susceptible to vibration and oscillation, resulting in a need to monitor and control the behaviour of larger structures (Wijst 1998; Stalmans 1999). The investigations that have been conducted in this area have predominantly been focused on the integration of piezoceramics actuators that demonstrate a higher frequency rate but a far smaller magnitude of movement than SMA actuators.

The areas of vibration and stiffness control are closely related. In both cases SMA wires are inserted into a fibre reinforced hard epoxy resin matrix. The reinforcing fibres most commonly used are carbon (Foreman, Nensi et al. 2007), glass (Choi and Lee 1998) and Kevlar (Parlinska, Balta et al. 2000; Stalmans, Tsoi et al. 2000). These supporting fibres offer high tensile strength and various amounts of rigidity depending on the proposed application. Although three to four times the diameter of conventional textile fibres, the small diameter SMA wires and thin films that are now produced (25 – 50 µm) mean the structural integrity of the composite is not lost (Stalmans, Michaud et al. 1998). To further reduce the impact of the SMA wire on the structure, the wires are usually integrated in line with unidirectional reinforcing fibres. The production of unidirectional composites minimizes the thickness and reduces uneven distribution of the epoxy or silicone which could weaken the structure (Barrett and Gross 1996; Parlinska, Clech et al. 2000). Stalman's investigation (1999) into the formation of resin pockets resulting from the integration of large diameter wires into composite structures, concluded that a 200µm wire could be integrated whilst still maintaining the structural integrity of a composite.

During the setting process of the resin the SMA wires are laced around a comb like structure that holds them in place between the layers of pre-impregnated fibre structures. The lacing of the comb determines the spacing of the SMA wire and subsequently the SMA volume fraction. During the curing process of the supporting matrix the comb can be used to pre strain the SMA wires if required. The strain recovery and transformation behaviour of the SMA wire is influenced and restricted by the properties of the matrix within which it is embedded (Stalmans, Tsoi et al. 2000). Increasing the number of wires or reducing the number of laminate layers increases the wire volume fraction, and as a result increases the recovery stress and activation potential of the wire in the matrix (Parlinska, Balta et al. 2000). Increasing the volume fraction by reducing the number of laminate layers, results in a tendency for the thin composites to buckle after activation of the SMA wire (Balta, Michaud et al. 2000) reducing rigidity, as well as the dimensional and structural integrity of the composite.

When investigating the control of multiple SMA wires through resistive heating, Stalmans (1999) connected the wires in series to ensure an even current and shape transformation. Heating the SMA wires produces large recovery stresses and increased elastic properties, that results in an increase in the bending stiffness and consequently shifts the resonance frequency of the host material (Balta, Michaud et al. 2000). The cyclic speed of SMA wires is further slowed compared to piezoelectric materials, when embedded in a composite matrix as they rely on cooling by natural conduction, which is ultimately determined by the heat transfer properties of the host matrix. For this reason unless the SMA is simply a superelastic material which does not require heating to influence the vibration resistance, the thermal SMA integrated composites are not usually suitable for high frequency vibration control. Thermal SMA can however be used for adaptive vibration control at lower frequencies as they can be activated independently from the stress incurred by the vibration. This independence means specific areas can be targeted irrespective of the external forces.

A method of overcoming the inherent limitation of cyclic speed in NiTi actuators for vibration dampening has been investigated by Srinivasan and Mcfarlan (2001) and was found to be suitable for many applications. The method involved the use of several NiTi wires in parallel. The NiTi wires were divided into subsets and energised in successive cycles increasing the overall frequency control of the matrix. It was noted that if the SMA volume fraction remained the same, but the number of wires in a subset increased to accommodate higher frequencies there was a corresponding drop in the control, recovery stress and activation potential of the wire in the matrix.

Choi and Rogers (Rogers, Liang et al. 1991; Choi and Lee 1998) discussed two additional variables to consider for the integration of SMA into composite structures for the application of shape control. The variables discussed were direct and indirect integration, resulting in direct and indirect shape transfer from the NiTi component to the structure. Although the means of integration would vary, the principles of manipulating the levels of freedom and restraint along the length of a NiTi component as an additional method of control, are pertinent to the aims of this thesis and the integration into textile structures.

Direct integration is when a NiTi component is placed directly between composite laminates and as such becomes part of a single structure; the SME of the NiTi can generate considerable force and control. The resulting interfacial relationship between the NiTi surface and the supporting matrix is critical to the efficiency of the composite and also the durability of the structure, as the bond between the matrix and NiTi may weaken over time and with repeated cycles especially if the wires have been pre-strained in the structure. Differing from direct integration, indirect integration has sections of the wire that are not directly influenced by or influencing the supporting structure. The method of indirectly integrating NiTi components can either involve the NiTi being anchored to the supporting structure at points along its length, or firstly inserted into a sleeve before being set within the composite matrix which allows movement. This method of integration allows greater freedom and independent movement between the NiTi component and composite matrix, reducing interfacial fatigue but also reducing the internal stresses of the composite. The patterns of shape transfer from the NiTi component to the supporting structures can differ greatly between direct and indirect integration. When embedded directly the shape transfer from the NiTi to the structure is to a greater or lesser extent a copying (direct transfer) of the trained form. Indirect shape transfer does not necessarily see the trained shape of the NiTi component transferred to the supporting structure but is used to initiate and often extend or exaggerate movement in the supporting structure.

2.5.2 Active shape control

For vibration dampening and stiffness control the SMA is constantly reacting to and correcting a force exerted on the composite. As a result of the constant force reacting on the SMA wire an additional return force is not required. With active shape control although the SMA is reacting against a force to increase control and frequency of movement, an antagonistic setup such as opposing two SMA actuators, can act as a pull-pull mechanism on the composite (Wang, Hang et al. 2008).

When embedded in hard epoxy based composite structures SMA wires can only effect limited shape change due to the restrictive nature of the matrix. To achieve greater levels of shape change and control, a number of methods have been investigated in the literature. In their review of active shape control using SMA wire in addition to vibration and stiffness control Simpson and Boller (1998) discuss two further areas; active shape control and robotics. Although adequate, this offers a limited view of the complexity and diversity of the mechanisms that have been investigated.

Table 8 expands the range of mechanisms discussed, based on a review of current research in the area focusing on the substrate and the method used to integrate the SMA wire as well as the form and level of movement produced.

Direct shape transfer	Quasi – static shape control	Embedding SMA wires in thin laminates of reinforced epoxy to reduce the influence of the matrix on the SMA shape change (Simpson and Boller 2008).
	Very low stiffness active composites	Embedding SMA wires either into an elastic substrate with a silicone or latex skin (Wang, Hang et al. 2008) or directly into a flexible matrix such as silicone (Barrett and Gross 1996). Often used in Biomimetic muscle structures.
Indirect shape transfer	Controlled buckling due to tilt force	Attaching the SMA wire externally to either end of a reinforced epoxy matrix beam (Chaudhry and Rogers 1991).
	Robotic shape control	Similar principle to the controlled buckling due to tilt force method but, instead of inducing buckling mechanisms, including joints and levers to regulate and extend the movement of the attached SMA wire (Sreekumar, Nagarajan et al. 2007).
	Active textiles	Integrating SMA wires into textile structures (Chan Vili and Stylios 2003; Berzowska and Coelho 2005) producing complex adaptive structures.

Table 8 Characteristics of direct and indirect NiTi SMA integration.

2.5.2.1 Quasi–static shape control

In beams that exhibit quasi-static shape control the SMA wire is set between a reduced number of laminated pre-impregnated layers compared to composites for vibration dampening, creating reinforced, semi rigid composite structures. This method of construction increases the SMA volume fraction, which as discussed further in section 3.2.6.1, results in the composite being more susceptible to the loss of dimensional stability. Quasi-static shape control has been investigated as a method of effecting shape changes in the sterns of submarines, aerospace control surfaces and wing profiles (Choi and Lee 1998). Investigations into SMA reinforced aerodynamic profiles date back to a project funded by the European Commission, entitled ‘Adaptive composites with embedded shape memory alloy wires (ADAPT)’ between 1998 and 2001 (Stalmans, Michaud et al. 1998; Stalmans 1999; Balta, Michaud et al. 2000; Parlinska, Clech et al. 2000). In this project a number of key issues were investigated including:

- Manufacturing procedures for integrating pre-strained SMA wires into Kevlar reinforced epoxy composites.
- Qualification and understanding of the interfacial relationships of SMAs encapsulated in a resin a matrix.
- Understanding of the functional, thermo-mechanical and durability properties, including type, surface condition, SMA volume fraction percentage, and the positioning of the SMA-wires.

The results from the ADAPT project have been used to inform subsequent developments. The reduction of drag and improvement of aerodynamic performance has a number of benefits for many forms of transportation particularly in marine and aerospace applications. The reduction of drag as well as achieving higher speeds would reduce fuel consumption, and increase operational range and endurance (Mani, Lagoudas et al. 2008).

Although successful adaptive panels have been developed and tested an issue that has prevented the scaling up of prototypes to manned aircraft is the number of actuators required. Based on the difficulties in scaling up the panels Simpson and Boller (2008) suggest that the future of adaptive aerodynamic profiles may not lie with conventional manned aircraft, but with smaller advanced craft such as unmanned aerial vehicles (UAV) or micro aerial vehicles (MAV). The advantages of UAV and MAV, from a design and engineering perspective, are that the inclusion of a human pilot does not need to be considered. With the removal of the human element, the structural and aerodynamic design of the craft can be optimised for the intended use, dramatically reducing the scale. The removal of the pilot from the craft also means the design can be optimised, working to the point of failure for the materials, which is considerably higher than it would have been for a human occupant. Many smart technologies have been utilised and developed for such craft and the reduction in scale is a major factor in this.

A different method of producing an active skin for UAV or marine applications, looks specifically at the reduction of turbulence and drag through the generation of a travelling sine wave and vortex-shedding on the surface of the active skin, rather than a direct change in the profile of the panel (Mani, Lagoudas et al. 2008). This method is based on very small movements producing a wave length of around 25mm and amplitude of around 30 µm. When the oscillating waves are of the correct length, amplitude and frequency a reduction in turbulent drag is achieved. The design of this active skin differs from embedding SMA wires in a composite matrix in that the SMA wires are attached to legs on the underside of the skin surface and on actuation the movement is subsequently extended. Integration of SMA wires in this manner produces a hybrid composite, combining the comparatively thin enclosed structural unit seen in directly embedded SMA, while utilising the extended movement seen in the exterior mounting of SMA wires in controlled buckling due to tilt forces (Figure 16). This hybrid method is described as a system that could be applied to a surface and as such is not part of the greater structural framework of the component.

[redacted]

Figure 16 Adaptive skin using actuated SMA wire (Mani, Lagoudas et al. 2008).

2.5.2.2 Low stiffness superactive composites

As described in 2.5.2.1, quasi static shape control is used to make small direct changes in the profile of a stiff structure enabling it to retain its surface and structural integrity while under air or water pressure. In contrast low stiffness composites utilise the low local strains of a matrix, to maximise the efficiency of shape transfer, from the SMA wire to the composite, rather than rigidity of the structure. The result of this is an easily deformed material, when the SMA element is not active.

Research into the production of artificial muscles has seen many developments that have focused on the production of shape memory polymers (SMP). As mentioned in section 2.2.1, electro chemical artificial muscles such as poly-electrolyte gels, ionic polymer gels and electro-activated polymers (EAP) all demonstrate the limitation of a slow response time which can be greater than five seconds, combined with a low useable force. In addition to these drawbacks, many of the chemicals used in the production of SMP are not bio-compatible. An alternative to SMP and EAP for development of artificial muscle structures are shape memory alloys (SMA). SMAs have an actuation response time that is dependent upon how rapidly they can be heated. This may be as low as a few milliseconds, which coupled with the potential useable force and bio-compatibility of NiTi SMA, is well suited to the development in active physiological muscle structures. The speed and force of the shape change in NiTi SMA can also be a negative factor, when considering SMAs as active material for integration directly into biological systems. When inserting SMA wires directly against biological tissue as in situ prosthetic devices or implants, the actuation strength of SMA wire is so high that the biological tissue will often yield and can be damaged when exposed to such forces. An additional problem faced by devices utilising the resistive heating of SMA is the higher temperature needed for actuation, which could damage local tissue. To reduce the impact of actuation forces and heat caused by resistive heating Barrett and Gross (1996) investigated setting NiTi within a soft malleable silicone matrix. The encapsulation of SMA into a malleable matrix reduces the impact of actuation as well as direct heat on surrounding tissue, whilst maintaining fibre stability and allowing relatively unimpeded movement during maximum deflection. This type of integration would be suitable for biomimetic, biomedical, surgical, prosthetic and other artificial muscle applications. Although heating to actuate an encapsulated, in vivo shape memory alloy device might require temperatures to rise above the established safe limit of 45 degrees Celsius, heat can be dissipated slowly by heat exchange between the SMA device and the surrounding tissue, reducing potential thermal damage.

The construction method of low stiffness composites has taken two distinct forms. The first is similar in structure to reinforced epoxy composites without fibre reinforcement. The SMA wires are embedded within a low hardness matrix, often silicone, where local strains are approximately only 1%. This method results in a very simple composite where the only interfacial stresses are between the wire and substrate. During their investigation of embedded SMA wire in soft silicone matrixes Barrett and Gross reported that as the number of cycles grew so the silicone matrix started to degrade. This allowed greater freedom of movement for the wire and consequently reduced the integrity of the structure. The damage to the structure was first seen at the point where the wire left the matrix and developed along the line of the embedded wire. This would appear to be a straightforward substrate fatigue problem, where the relatively large movement of the SMA element within a homogeneous structure and temperature differences causes the release of the wires to.

An alternative method of construction mimics the structure of muscle fibres; cross connective tissue and skin is used by many marine animals for propulsion. Using this naturally inspired structure Wang, Hang et al. (2008) attached SMA wires to both sides of a elastic polyvinyl chloride substrate with a thickness of 0.25mm, emulating the attachment of muscle fibres to connective tissue. The wires were placed antagonistically to increase the operational frequency to over 2 Hz. Latex and silicone protective skins were applied over the prototypes and tested for suitability. It was concluded that the ability of silicone to withstand temperature changes ranging from -60 to +250°C, better thermal conductivity and an ability to adhere to metal and plastic without separate adhesives, made it a more suitable and versatile material for use as a protective skin.

Bio-mimetic muscular structures that use active SMA wires have resulted in the development of methods of propulsion that can be used for the production of small silent running underwater vehicles. Like aerial vehicles the biomimetic muscles have been successfully used in small devices but not as yet in full human scale applications. These devices would be used to explore underwater environments and it has been proposed that they could in future be further developed for minimal invasive *in vivo* examination and micro surgery (Kim, Kim et al. 2004). The design of these devices has been based on the methods of propulsion and patterns of movement utilised by marine animals, including studies of muscle structures, movement and how these could be adapted to synthetic devices. To study the mechanisms and effectiveness of different forms of aquatic propulsion the SMA wires were placed in a number of test configurations. Oscillatory and undulatory patterns of movement were investigated with the wires placed either perpendicular or parallel to the axis of the body and direction of movement.

An application that uses a very different method of construction for setting SMA within a flexible structure was investigated by Veeramani, Buckner et al. (2008) in the design of an SMA actuated catheter. The investigation focused on actively controlling the tip of the catheter, so aiding the delicate and often complex navigation of the catheter within the patient. The design was built round a central NiTi tube which exhibited elastic behaviour at room and body temperature (20 – 35 °C). The central tube acted as an antagonistic muscle for an offset tendon which was a 0.127mm ‘Flexinol’ wire from Dynalloy Inc. attached by collets at either end. The assembly was encapsulated in a Teflon sleeve. The wire and tube were connected at the tip for electrical continuity and to a power supply at the other end. The research demonstrated that by altering the electrical current applied to the wire the bending angle of the catheter could be controlled between 0 and 80°, while conforming to circular arcs of deflection.

2.5.2.3 Controlled buckling due to tilt force

Although described as ‘tilt force buckling’ the mechanism investigated by Chaudhry and Rogers (1991) falls just short of actual buckling. Externally mounted and offset SMA wire actuators demonstrate much more control due to the differential movement between the beam and actuator. Before the point of actual buckling there is a range of movement that can be utilised, where beam deflection is still controllable and recoverable. This configuration results in an increase in the structural integrity of the composite resulting in the ability to withstand greater deflection before buckling. An additional advantage of externally mounting the SMA wire is a faster cyclic speed, resulting from the improved convection cooling of the wire after thermal activation. Shu and Lagoudas (1997) used two antagonistically operated SMA wires to further control and increase the cyclic speeds of a beam’s movement. In the same way as the interface between SMA wire and composite matrices is important in embedded composites, the positioning of externally mounted SMA wires is also critical. The wire must be secured to prevent any movement, yet care must be taken to prevent damage and reduce fatigue at the interface between static and moving parts.

In their research Chaudhry and Rogers (1991) determined that if externally mounted wires pass through an additional point along the beam, the two sections of wire behave independently to each other. The additional point of connection can be used to effectively tune the movement of the beam. When the SMA wire is actuated, the shorter section of the beam remains straight while the longer section bends. Simply by altering the position of this additional point of contact different bend profiles can be achieved. If the position of the point of contact cannot be actively moved, multiple wires can be attached along the beam and independently stimulated to effect different shape changes. Adaptations of this method of controlling the shape of a beam or surface offer many possibilities of secondary control to the textile designer.

2.5.2.4 Robotic shape control

The dictionary definition of ‘robotic’ is **“**any automated machine programmed to perform specific mechanical functions in the manner of a human” (Collins 2004). When analysing the mechanisms discussed in the previous sections, the descriptor ‘robotic’ could be applied to any of them, being used as a generic description. In this context, the descriptor ‘robotic’ is used based on a review of the available literature regarding actively controlled SMA wires. Although not specifically defined, a consensus for the use of the term ‘robotic’ seemed to have been reached in the field. The mechanisms that were described as robotic, use mechanical forms of articulation, comprising at least two separate components in addition to the SMA wire that initiated the movement. The components used were inflexible on the scale employed, relying on mechanical articulation rather than the flexing of a single component.

The use of SMA wires for robotic applications has focused on both prosthetic and industrial systems for sensing, gripping and manipulating objects. Motorised, pneumatic and hydraulic systems are still generally used for large scale applications, appropriate to the scale and dexterity of components. Although small servo and stepper-type motors give good patterns of movement, they are comparatively bulky and may require complex electronic control systems, when considered for applications like dexterous robotic hands (Brown, Tsagarakis et al. 2007). Reducing the size and weight of these units has led researchers to actuators such as electro active polymers, McKibben pneumatic artificial muscles and SMA. Electro active polymers have seen some success in small light weight devices, but the use of pneumatic artificial muscles in small scale applications has been limited due to the need for compressed air and mechanical electrical valves (Price, Jnifene et al. 2007). The use of artificial tendons has allowed the removal of bulkier actuators and components to areas of the device where size is less critical nevertheless; controllers and ancillaries are still required, limiting or constraining design and miniaturisation. SMA actuators have been more successful when the wires act as a combined muscle / tendon, making direct attachment possible reducing the size of the actuator system. The advantages of SMA actuators include a high power to weight ratio, silent running, minimal moving parts, reduced friction, potential for feed-back signals (change in electrical resistance as strain is increased/decreased), and simplified maintenance. The reduction in scale sees another benefit from SMA as miniaturisation improves cyclic speed of the actuator as a result of a higher surface to volume ratio. The development and design of the majority of dexterous robotic hands and grippers can be traced back directly to the anatomy of the human hand and arm. Although the number of segments may exceed the three phalanges and one metacarpal for each digit in the human hand (except the thumb which does not have an intermediate phalange) the same principle of jointed segments articulated by a ‘tendon’ is widely used. An early example of a robotic hand using SMA wires can be seen in the Hitachi Robot hand of 1984. This device was designed to emulate the human hand in the flexible manipulation of objects (Marcincin and Smrcek 1997).

The linear arrangement of positioning SMA wires mimics the systems of joints and tendons seen in nature (Figure 17 a). This configuration is sometimes abandoned in favour of a transverse arrangement (Figure 17 b). The transverse arrangement demonstrates the benefit of reducing the SMA wire’s contact with an encapsulating skin, decreasing wear; if left exposed, the wires would be more susceptible to damage or being dislodged. An additional benefit of the transverse arrangement is that, due to the increased length of the SMA wire, there is a corresponding increase in the maximum joint deflection for a given strain (Price, Jnifene et al. 2007).

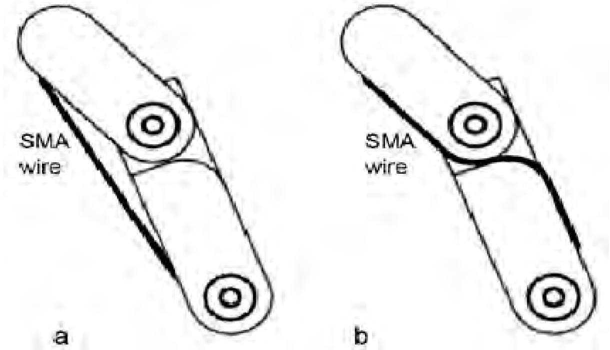


Figure 17 Arrangements of SMA wire in simulated finger joints. a. Linear b. Transverse.

As a result of scale, it is not always appropriate to use a joint and tendon configuration for the design of robotic grippers. An example of this is the SMA micro gripper developed by Kohl (2002). At just 2mm x 5.8mm x 0.23mm, including an integrated optical positioning sensor providing accuracy of about 2µm, this gripper works with a very simple mechanism (Figure 18). The maximum stroke of the gripper is 300µm which can be achieved within 140 ms providing 35mN of force. Micro grippers are used in minimally invasive surgery where they are delivered inside a suitable catheter with diameters of between 4 mm and 12 mm. Alternatively, rigid, flexible or steerable endoscopes are used, to deliver or deploy drugs, devices or take biopsies (Sreekumar, Nagarajan et al. 2007).

[redacted]

Figure 18 Schematic of micro grippers (Sreekumar, Nagarajan et al. 2007).

2.6 Active textile structures integrated with NiTi components

This section investigates three areas of development that utilised the properties of textile structures for the production of SMA composites. Within these areas, direct comparisons can be made with the shape control mechanisms discussed in section 2.5. The ability of textiles to adopt and extend the different mechanisms used by non textile based SMA composites demonstrates that rather than being restricted to a few specialist areas the use of active textile structures can extend the range of possible applications. The production of a textile structure that can demonstrate integrated reversible shape control, flexibility and semi-rigidity offers the textile designer greater opportunities to adapt a combination of functional and aesthetic properties. These new structures demonstrate effective improvements in functionality that could not as easily be produced through non-woven structures (Boussu, Bailleul et al. 2002). 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.

A factor that has limited the use of SMA actuators in the development of shape controlled textiles is the need to train SMA wire at a high temperature. As discussed in section 2.3.10.1 the training temperature is usually between 425 and 500 °C. This exceeds the usual working temperatures of most textile fibres. The exceptions are carbon and glass fibres (Stylios 2006) but these are unsuitable for apparel and close contact with skin. For this reason research to date on the integration of shape memory alloy wires as the primary method of control in woven structures has focused on the wires being trained to a uniform shape prior to insertion into a woven structure, for example straight or coiled forms. Although information is limited due to a patent pending the Pan European Project Avalon (Reade 2009) has recently announced the development of a heat setting process at 200°C which would improve the compatibility with integration into textiles. In addition to the primary control of the SMA, the interaction between the SMA, yarns and woven structures allows a secondary level of control to be achieved. This additional level of control can be used to facilitate, extend or impede the influence of the SMA wire across the textile in a similar fashion to the wing of an insect which is only controlled by muscle at the root (Sunada 2008). Structural differences across the wing enable it to react in different ways. The influence of the root muscle and air pressure create complex deflections without direct muscular input. For this reason an understanding of the interaction between the SMA wire and the host structure is critical since proposed applications require a transfer of force from the wire to the woven structure. This control mechanism can also be seen in the development by Chan and Stylios (2003) of SMA and SMP composite yarns. They found that when wrap–spun, an increase in the twist of the conventional fibres around the SMA or SMP core inhibited the SME.

2.6.1 Structural integrity and impact resistance using woven NiTi wire

The construction of these composites is very much like non-woven fibre reinforced vibration and stiffness control composites discussed in section 2.5.1. The woven SMA structures are embedded in a rigid matrix of glass or carbon fibre epoxy pre-impregnated layers. In the woven composites the NiTi wires are laid down within an interlaced bi-directional structure where the NiTi has a pre-determined spacing dependent on the sett of the material. Unlike unidirectional structures there is no need to space the wires using a comb which means the NiTi can more easily be placed between layers of reinforcing fibres and resin. To investigate the quasi-isotropic properties of a composite beam that incorporates a woven NiTi structure Boussu, Bailleul et al. (2002) produced a series of samples to demonstrate and compare the properties of a NiTi wire woven with a conventional yarn as well as on its own creating a 100% NiTi woven mesh. These results were compared to a similar woven mesh that used a comparable stainless steel wire.

Boussu's initial weaving study was conducted to demonstrate the weavability of a textile incorporating NiTi yarns and to evaluate effective improvements in the properties of the composite. A plain weave structure was used to provide improved stability of the mesh and a 150µm SMA wire was chosen as it offered a good compromise between the efficiency of the SMA and the thickness of the composite. The fabric was sett at five threads per cm resulting in an open mesh. Although some weaving defects were seen in the samples combining conventional yarns with NiTi wire, the overall weavability of the NiTi was better than stainless steel. In a comparison of tensile strengths between a woven sample incorporating twenty three NiTi wires and an equivalent number of non-woven wires, an increase in stress of 0.1GPa was observed, demonstrating that the wire had not been damaged as a result of the weaving process. This research also demonstrated that it was possible to increase elongation by 5% at maximum stress; complete failure of the fabric did not occur until elongation reached 10%. The increased elongation to maximum stress was a result of the un-crimping of the wire in the woven structure under stress. Future evaluation was proposed including damping and impact testing as well as the exploration of 3D shape control capabilities and investigation into the influence of a denser weave structure.

2.6.2 Impact resistance

At QinetiQ, Foreman, Nensi et al. (2007) and his team focused on improving the relatively poor impact resistance of polymer matrix composites. Foreman et al. utilised the lower density for high strength and dampening properties of NiTi SMA in a woven structure to optimize the material's specific properties. Initial samples of SMA meshes were produced on a hand loom to demonstrate the concept and performance of different SMA materials. This method of production was soon dismissed because of the complexity and the cost of production. QinetiQ approached Sigmatex UK Ltd., in Runcorn, to investigate the feasibility of developing a fully integrated SMA carbon fibre material. Initial results demonstrated difficulties in the weaving of the SMA due to its springy nature and tendency to twist in the textile. The difficulties experienced by Sigmatex were similar to those encountered by Boussu (2002; 2006). Boussu noted that for a 100% Nitinol fabric special measures must be taken during warping, threading and weaving to keep the NiTi in the Austenite phase. Many of the problems encountered during the weaving of SMA wire were a result of low strains, reduced stretch and flexibility compared to conventional spun yarns. In comparison to stainless steel, Boussu found NiTi produced less weaving defects and in Chan's investigation it was found that the NiTi behaved in a similar way to a monofilament yarn (Chan Vili 2007). As a result of advanced weaving techniques including the optimisation of weaving variables and the development of specialist fibre handling equipment Sigmatex was able to produce high quality fabrics. Sigmatex produced a range of carbon fibre fabrics using different wire types including ribbon, as well as different SMA volume fraction, that varied by the number of wires in the warp and weft directions.

In most of the samples produced for testing a resin film infusion was interleaved between layers of untreated plain fabric or fabric with integrated SMA wires before curing in a pressure assisted autoclave. After the initial development a number of samples were produced by Hexcel Composites, UK producing a pre-impregnated variant of the woven SMA carbon fabric. All the samples consisted of four layers in a 0/90/90/0 layup in a variety of plain and SMA fabrics (Foreman, Nensi et al. 2007). Based on the results of impact and lightening strike testing Foreman et al. concluded that the SMA / carbon reinforced composite had demonstrated superior properties when compared to commercially available materials. When the SMA / carbon fabric was placed as the outer surface of the laminate and then exposed to simulated lightening strikes the degradation of the structure was prevented. The results from the impact testing showed that the SMA / carbon composites demonstrated improved impact resistance and that this was not dependent on the positioning of the SMA / carbon fabric in the composite. The superior properties of these composites will allow a reduction in material and consequently weight when designing and producing new components.

2.6.3 Active shape memory textiles

The development of woven composite materials for use as structural / vibration control components is more advanced than that of shape memory applications as it is building on already established products. Another factor that is important when considering the development of these two distinct areas is that the interfacial relationships are less complex in structural / vibration control applications as the fibres are held in a rigid matrix. As discussed in section 2.5.1, active vibration and stiffness control is constantly attempting to maintain the stability of the material rather than trying to distort it as is the case with active shape control. A result of this fundamental difference in outcomes is that quasi-rigid composites like reinforced epoxy are not suitable substrates for the promotion of large movements or displacements. For this reason SMA are integrated into flexible structures such as silicone. Although silicone is able to flex with the movement of the SMA due to the localisation of the interfacial stresses (section 2.5.2.2), the SMA quickly loses continuity within the silicone during repeated cycles and breaks free from the matrix. As discussed in section 2.1.2.1 the ability of a textile structure to deform easily, spreading forces across its lattice structure, suffering large strains and displacements at low stresses whilst maintaining structural integrity makes it an interesting substrate for consideration as a supporting structure for active shape control material (Adanur 1995). Modifying the stiffness and elastic behaviour of an inherently flexible material from a malleable deformed shape to a pre-programmed shape will produce a highly adaptable material.

The attachment of pre-trained SMA wires to the surface of a polyester micro fibre cylinder using sophisticated computer controlled embroidery techniques has been used commercially since the mid 1990s where the specific properties of the composite advanced developments in surgery techniques for the treatment of cardio vascular aneurisms in the form of graft cardio-vascular stents (Anson Medical 2009). The embroidery of NiTi onto textile structures has also been investigated by Berzowska for aesthetic rather than task driven applications (Berzowska and Coelho 2005). Using both direct embroidery and felting techniques Berzowska created flower like brooches that opened and closed their felted petals with changes in temperature, and a dress, the hemline of which could be retracted (effectively shortened) by the activation of NiTi wires stitched to a soft cotton panel. Although not commercially driven these examples clearly demonstrate the potential of adaptive shape memory textiles in functional and aesthetic markets.

Grande Zero Space, an Italian technology transfer research organisation (Grado Zero Espace 2009) were the first to commercially integrate NiTi shape memory alloy in a woven structure which is commercially known as Orica. Awarded “Best Invention” of 2001 by Time magazine the fabric Through the European Space Agency (ESA) Technology Transfer program (TTP) (ESA 2003; Braddock and Mahony 2005) Corpo Nove (2008) developed a shirt using the Orica shape memory fabric that performs two functions. The first function utilised the SMA wires interspersed between nylon yarns in the warp of the cloth so that low level heat, for instance from a hair dryer, it would return the SMA wires to their trained shape. It is claimed that the use of the shape change properties in this manner removed the need to iron the shirt. The second function was the active shape change of the sleeves which rolled up when the ambient temperature reached the Af temperature of the SMA wires. Instead of being integrated within the woven structure producing a truly integrated SMA textile the SMA wires in the sleeves were simply stitched in place.

Consisting of nine partners across five European countries, the Loose and Tight project (EU. project Loose & Tight 2009), funded by the European Commission and encompassing the whole supply and production chain, investigated the concept of graduated compression hosiery. The project set out to develop and optimize procedures for the production of hybrid yarns and textile structures for processing using current textile machinery. Other aims of the project were to maintain the superelastic properties of fine NiTi wire during production, and the subsequent development of a numerical model capable of predicting the constant compression loads along the leg generated by the composite fabric structure. To facilitate maximum stretch within the textile a knitted structure was used with the fine NiTi wires being interlaced within it.

The doctorial thesis of Yvonne Chan (2004) is the most extensive research published on the integration of SMA into woven textiles for shape memory applications. The research focuses on the subjective evaluation of the aesthetics of shape memory textiles for interior applications. The preliminary research by Chan (2003; 2004) investigated, through a range of systematic trials, the spinning of fancy yarns incorporating SMA wire and SMP monofilament using a Gemil and Dunmore fancy wrap spinner producing core wrapped yarns. The spinning performance of Superelastic NiTi wire with diameters between 200μm and 300μm was tested to produce a composite yarn prior to weaving. The rationale for the creation of SMA composite yarns was to improve the visual and tactile properties making them more appealing as yarns for apparel and interior applications. From the initial trials it was discovered that high twist levels of between 150 and 250 wraps per metre produced an even and dimensionally stable yarn but this needed balancing to maintain an effective SME. At low twist rates there was a reduction in the adhesion between the yarns and the wire core resulting in wire protruding and not remaining in its position at the core (Chan Vili 2007).

Initial woven samples using conventional yarn as support for the SME integrated an SMA wire trained into a coil in the woven structure. For the shape change effect to be noticeable on the surface it was decided to loosely sett the samples at twenty eight EPI in a plain weave so as not to restrict the SME. To optimise the coil effect of the yarn, samples were woven with variations of floats and quantities. Initially, on stimulation of the sample the effect seen was a general contraction of the textile rather than a gentle coil. It was also discovered that after a number of cycles the SMA started to break out of both the yarn and weave structure. For later samples both the composite yarn and woven structure were reviewed.

In addition to the samples using simple coil trained SMA wires, Chan produced woven samples on a tapestry loom where both the warp and weft used SMA wires of 200μm diameter. These samples were developed to demonstrate the types of shape change that could be produced in a composite textile if the supporting yarn was able to accommodate the high temperatures needed to train the wire. The 100% SMA textiles woven by Chan were then manipulated by hand before being restrained in a special jig during heat treatment. Once trained these samples produced a simple switch motion between the malleable low temperature state where the fabric could be flattened or distorted, changing to the programmed form on heating. As a result of the under setting at approximately thirteen EPI the structure was quite unstable and there was movement of the wires in the mesh. Later samples produced on a hand loom were set at approximately twenty four EPI which demonstrated better if not total uniformity and stability across the samples.

There are a number of other sources relating to the integration of SMA into woven textile structures including a number of patents. The earliest patent Steckmann and Prieb (2002) simply describe any flat woven textile structure incorporating SMA for use in the areas of medical, aeronautical and space technology application. For medical applications a range of compressive and stabilizing devices are described. The latest patent was granted to Phillips for the invention Waxler (2007) describes as the integration of SMA into woven structures that are capable of adjusting the surface area and the contour of a fabric. The patent discusses how the shape change of the material could be adapted to a variety of apparel applications. An example is the change of size and style of a garment demonstrating an adaptive one size fits all method of attaining the correct fit. Neither patent refers to any experimental prototypes nor feasibility studies for a proposed method of production.

Continuing on from the work of Chan on the spinning of composite yarns that incorporate SMA for woven textiles, Winchester (2003) developed yarns for integration into knitted structures. The principle aim of this research was to develop “living” fabrics that exhibit different aesthetics in the same cloth. The knitted structure was used to create expanding sections that extended existing 3D forms.

A number of other unpublished studies that have investigated the integration of SMA into both woven and knitted textile structures for very specific ‘one off’ applications or as part of college projects often looking at integration on a surface level. One project by Saul Griffith, while an undergraduate student at the media lab, which is part of the Massachusetts Institute of Technology (MIT), in 1999 investigated the integration of 25µm and 100µm SMA wires into a knitted glove to provide tactile force feedback to the wearer (Griffith 1999). There is limited detail of the specific parameters or methods for the production of the glove but from images it seems that it was constructed from a medium weight yarn that would allow considerable movement of the wire in the structure. In spite of the far from optimised construction it was reported that sensory feedback was achieved.

2.7 Conclusion

The review of literature has identified key aspects relating to the research questions from within the broader knowledge base and has established the theoretical foundation from which the research has been developed. The relationship between the research questions stated in section 1.2 and the study’s’ interdisciplinary nature was investigated and the limitations and gaps within the current body of knowledge were identified. Setting the area of study in the wider field of material science and engineering, specific characteristics, developments and the potential of textiles were discussed as was their relationship to biomimetic and sustainable design principles. The area of *smart* materials was also discussed including issues of clarity concerned with the creation and description of a hierarchical structure relating to *passive* and *active* materials. From this discussion of material types the area of active shape memory materials was broadly evaluated followed by a focused investigation into NiTi SMM covering aspects of its history, development, mechanical properties and processing. The final part of the chapter was concerned with the identification and evaluation of passive and active mechanisms and applications utilising the specific properties of NiTi SMA. Due to the limited literature on the creation of integrated NiTi textile composite structures other fibre structures, as well as non fibre based flexible and rigid NiTi composites were investigated, with comparisons and differences identified and discussed. Based on current research in both the direct and adjacent areas of active NiTi composite structures these final sections have laid the groundwork for the materials and methods that will require investigation and are discussed in the subsequent chapters.

3 Materials and Method

Following on from the definition of the surrounding and specific areas relevant to the investigation in the literature review, this chapter draws the focus onto the specific research questions and the methods employed to answer them. Starting with an overview of issues relating to the evaluation of active NiTi textile structures, the three phases that make up this investigation are clearly set out in Figure 2. The remainder of the chapter is concerned with the first phase of study which isolates, discusses and evaluates the compositional variables and procedures used for the production of the samples, concluding with the setting out of the testing procedures and methods of recording the resulting data.

3.1 Evaluation of active NiTi textile structures

The literature on the integration of NiTi SMA wire into woven structures is not extensive and to date there are no clear published guidelines for the design and optimisation of dynamically controlled, NiTi integrated, active woven textile structures. As a result many basic questions require investigation before the relationship between NiTi components, supporting yarn and the supporting structure can be better understood. Design methodologies for embedded sensors and actuators in structures, especially composites including textiles, are at an early stage of development and are often based around the component rather than the host material (Uotila, Mattila et al. 2006). When investigating the integration of an active material like SMA into textile structures traditional methodologies are often inadequate and unable to accommodate the new and variable properties realised in the host material. The development of a clear and comparable test method to investigate 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. The novel and interdisciplinary nature of this area has necessitated the development of a method of enquiry which combines materials testing approaches from both textiles and material science disciplines.

As part of the investigation into interdisciplinary research and specifically 'the intelligent garment as a research object' the recent project, 'Methods and Models for Intelligent Garment Design (MeMoGa) identifies three independent research disciplines needed for the design of smart or intelligent garments (Uotila, Mattila et al. 2006) (Figure 19).

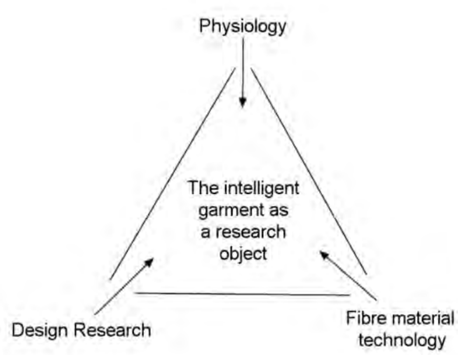


Figure 19 Three disciplines identified for the development of intelligent garments.

An early discussion on design methodologies for the development of active materials and adaptive structures by Barsoum (1997) at the Office of Naval Research, USA, was based on design methodologies relating to composite structures with embedded sensors and actuators. As part of this investigation two key issues were identified that would need to be addressed from a basic research point of view.

i. The passive – active interaction and coupling of mechanical, electrical and thermal behaviour on the structural level.
   a. Control theory, energy requirement, consequences of loss of active control and system efficiency.
   b. Reliability of integrated actuators and their integration with the host material.

ii. The optimisation of size and location of sensors / actuator based on control theory, structural response, and desired adaptability.
   a. Actuator behaviour (linear versus nonlinear response).
   b. Control methodology (linear versus nonlinear control).
   c. Optimization technique.

The work of Chan (2004) has progressed the area and demonstrated the fundamental proof of the concept of active control of woven textiles through the integration of NiTi SMA. This study goes deeper and focuses on underpinning the area for future research and development. Through a systematic and rigorous investigation, it explores how the manipulation of specific variables in woven composite structures can be used to not only maximise direct shape transfer from an integrated NiTi component, but also to effect different levels of indirect shape transfer along a uniformly trained NiTi component. Given the relatively undocumented nature of this area of research it was decided that it would be unwise to focus primarily on mechanisms of movement and end use as these would necessitate numerous assertions and assumptions in the selection of materials and structures. Without a developed and informed appreciation of the fundamental relationships and properties underpinning this area of research, an accurate understanding of the composite would not be attained.

3.1.1 Structure of methodology used

To manage the range of variables being investigated a systematic framework (appendices B) for the production of samples was created, with each sample focusing on a specific combination of variables that fitted within and complemented the whole. Using this framework of repeated patterns of variables aided the comparison and evaluation of results and lessened the necessity to perform multiple tests on samples with the same selection of variables, as inconsistencies in testing could be identified from the evaluation of patterns gained from the overview of results. This strategy meant that a wider range of variables could be explored thus informing the broader area. Carried out in three clear phases (Table 9) the outcomes of this research initially followed a subjective and theoretical methodology that was later tested in phases two and three by a selection of specific objective measurements to characterise and evaluate the performance of the NiTi when inserted into a textile structure. The empirical approach investigates the integration of SMA actuators into woven structures and focuses on how the functional properties, movement and constriction are affected by variables such as woven structure, sett of fabric, supporting yarn, and the cross sectional area and surface treatments of the NiTi wire.

	Focus	Test method	
Phase 1			
Identification and initial assessment of variables	Method Yarn Structure EPI NiTi	Evaluation of current evidence SEM	Theoretical
Phase 2			
Study i Visual and tactile evaluation of NiTi and weavability	Woven structure Ends per inch Yarn NiTi	Visual Tactile	Empirical Qualitative Subjective
Study ii Introduction of selvedges to cover wire ends	Woven structure NiTi	Visual Tactile	Empirical Qualitative Subjective
Study iii Influence of selvedges on NiTi wire extraction (using mechanical mass loading method)	Woven structure Ends per inch Yarn NiTi	Visual Tactile Bend testing Tensile test (Wire extraction)	Empirical Qualitative Subjective Quantitative Objective
Phase 3			
Study i Influence of fabric density (EPI) and integration of Duron on NiTi wire extraction (using mechanical mass loading method)	Woven structures Ends per inch Yarn NiTi	Bend Tensile test (Wire extraction)	Empirical Quantitative Objective
Study ii Influence of the yarn and woven structure on NiTi wire extraction (using mechanical mass loading method)	Woven structures Yarn NiTi	Bend Tensile test (Wire extraction)	Empirical Quantitative Objective
Study iii Influence of the yarn and woven structure on NiTi wire extraction (using computer controlled tensile / compression testing machines)	Woven structures Yarn	Tensile test (Wire extraction)	Empirical Quantitative Objective

Table 9 Overview of work carried out in each study.

3.2 Phase 1. Identifying and initial assessment of variables

Focus:
The theoretical evaluation of variables:

- Supporting Structure
  - Yarn
  - Structure
  - EPI
- NiTi
  - Dimensions
  - Section
  - Finish
  - Training
  - Trained shape
- Test Method
  - Evaluation
  - Theoretical
- SEM
- Equipment
  - Loom
  - Mechanical mass loading method
  - Computer controlled tensile / compression testing machines)
  - Oven

The first phase of the investigation identified and evaluated physical, material and structural variables, as well as less tangible, emotional responses that will influence research in the field of active shape memory textiles. The complex material, structural and resulting interfacial relationships arising from the combination of fluid movement and active control meant it was important to define the different aspects of active shape memory textiles as a means of understanding the potential and limitations of proposed applications. The first step in the development of a clearer understanding of the area was drawn from concepts presented in the literature as well as my own personal knowledge and experience of textiles and the articulation of rigid materials. To achieve this, a number of methods of tabulation were employed including an expanded referenced visual overview of this emerging field (appendix A.). From this overview individual elements and variables were investigated and evaluated.

3.2.1 Supporting structure

The choice of supporting textile structure was addressed at an early stage. The type of textile structure would govern the resulting applications as well as being fundamental to the accurate transfer of control from the NiTi wire to the textile and as such the production of repeatable dynamic patterns of movement. The review evaluated the three main textile construction methods; woven, knitted and non-woven structures. Barsoum (1997) identified four mechanical characteristics as being key to the successful development of active textile structure using NiTi wire.

The four characteristics identified were;

- The suitability of the wire for processing into the structure
- The ability to accurately integrate the wire
- The accurate transfer of the trained NiTi form to textile structure
- The durability of the structure as a result of the integrated NiTi wire.

The need for a reliable interface between the wire and the textile structure meant that these characteristics would need to take precedence over the emotional or subjective properties although it was important that any decisions were still related to the fundamental textile properties of flexibility and adaptability. In addition to the structural considerations a diverse range of physical and emotional quantities and subjective factors were identified in appendix A. These would also need to be taken into account for the successful integration of SMA wires into either apparel or industrial textiles.

3.2.1.1 Knitted structures

The knitted structure is made up of successively inter-looping yarn in connecting vertical columns (wales) and horizontal rows (courses) (Figure 20) producing a highly adaptable and formable structure with inherent elasticity. A knitted structure would be suitable for the integration of regularly trained wires like coils which can demonstrate expansion and contraction characteristics (Winchester and Stylios 2003). The meandering path the NiTi wire takes in the knitted structure would not be conducive to the accurate insertion needed for the transfer of simple arcs or wave forms from the wire without a dramatic distortion to the stitch pattern. To achieve either of these forms the NiTi wire would require training after insertion into the knitted structure but in this configuration additional attention would be needed to stabilise and secure the wire in the structure. As discussed in section 2.3.10.1, due to the high temperatures required for the training of NiTi wires, if training is to be conducted after the integration of the wire either the resistive underwater heat treatment developed by Anson (EU. project Loose & Tight 2009) or supporting yarns tolerant of very high temperatures would be required which would result in poor tactile properties'. A further complication to the post insertion training of a knitted NiTi structure would be the accurate placement of the textile on the restraining jig due to the structure's natural elasticity.

[redacted]

Figure 20 Plain knitting structure (Adanur 1995).

When being inserted into the knitted structure the wire would undergo a complex succession of bends and manipulation to produce the stitches. These additional mechanical forces would affect the wire's shape memory properties and also increase stresses as they draw near their minimum bend radius (Table 10).

Flexinol Wire Diameter (µm)	25	50	100	125	150	200	250	300	375
Minimum bend radius (mm)	1.25	2.5	5.0	6.25	7.5	10.0	12.5	15	18.75

Table 10 The ratio of bend radius to wire diameter for Flexinol wire is 50:1 (Gilbertson 2000).

3.2.1.2 Non-woven structures

Produced by means other than weaving or knitting, non-woven fabrics are usually manufactured by laying down web-like fibre structures which are then processed to create a cohesive, bonded fabric. The classification of non-woven textiles is often by the method of web preparation or bonding of the fibres (Table 11).

Web formation		Bonding technique
Mechanical		Mechanical
Fluid: air, water		Needle punched
Electrostatic		Chemical
Film extrusion		Adhesive
Felting		Heat

Table 11 Non-woven structures, formation and bonding technique.

Due to the production techniques non-woven textiles offer a wide range of benefits for the integration of linear and especially non linear NiTi components as they can be encapsulated undistorted by the web rather than needing to conform to a woven or knitted structure. In many of the standard manufacturing processes the encapsulation of the NiTi could occur during the production of the web but care would need to be taken when considering production methods such as heat bonding, or other methods where the web requires a heating process during production, as this could initiate shape change in the NiTi resulting in misalignment and premature distortions of the fabric.

A process for producing non-woven shape memory textiles was investigated by Berzowska. Fine NiTi wires were positioned between thin layers of wool fibre prior to a felting process (Berzowska and Coelho 2005). This encapsulation of the wire facilitated its insulation from the wearer and created a seamless soft circuit. An additional benefit of using felted wool as a supporting structure for NiTi wires that are to be resistively heated is its self extinguishing fire resistant properties which prevent it from catching light.

Although non-woven textiles can be produced as very thin, highly flexible materials, the fabrics often have poor draping characteristics and hand due to the limited movement between the fibres in the web. This stiffness between the fibres can be utilised as a mechanism and return or bias force to deform and as long as sufficient force is used to activate the structure. Despite these restrictions non-woven textiles integrated with NiTi components have the potential to play an important role in the future developments of shape memory textiles.

3.2.1.3 Woven structures

Woven textiles are the most widely produced textile structure and consist of the perpendicular interlacing of parallel warp threads, also known as ends, with weft threads, also known as picks or filling. Having greater dimensional stability than knitted structures when force is exerted in line with the warp or weft, they only demonstrate low levels of distortion which, when occurring, is due to the elasticity of the yarn or the tightening of the crimp of the yarns in the cloth. In contrast to this stability, the distortion seen in the simulation in Figure 21 shows a fabric subjected to shear or bias forces equivalent to 0.49 Newtons. When hung on the bias, a woven fabric can undergo noticeable elongation and distortion, improving the drape of the cloth resulting in the material more closely conforming to the underlying form. The stability of the woven textiles can be manipulated by changes to the structure and yarns used, facilitating or impeding the interfacial movement between the individual warp and weft threads and the resultant drape of the fabric. The production of woven structures offers a range of variables that can provide a controlled yet flexible, adaptive structure. These properties are discussed further in section 3.2.2.

[redacted]

Figure 21 Simulation of fabric under diagonal (bias) tension (Hu 2004).

3.2.1.4 Summary of textile structures

The evaluation of textile structures focused on the accurate and stable integration of NiTi SMA into textiles produced using woven, knitted and non-woven textile construction methods. All three structures demonstrate specific attributes that can be drawn on and utilised in future developments. Notable advantages in the use of knitted structures are the inherent elasticity and formability that can be utilised in applications where large levels of expansion and contraction are required. Non-woven structures could be utilised to great effect where complex non-linear forms are required or for direct integration into three dimensional structures, but where the drapability and handle are less critical.

When considering the criteria for the development of active textiles capable of producing accurate, repeatable, controlled patterns of movement, the properties of woven structures demonstrate a number of distinct advantages. They are able to accommodate the accurate integration of a NiTi wire as well as the creation of repeated patterns that can demonstrate different interfacial properties. As a result of this evaluation woven structures are the focus of this investigation.

3.2.2 Variables in the production of woven textiles

The following section will identify, evaluate and discuss these variables in conjunction with the benefits or attributes they could offer for the production of controlled patterns of movement in woven structures. The grid structure of woven textiles offers a wide range of physical, mechanical, visual and tactile properties that can be produced through the choice and manipulation of the woven structure, yarn and sett of the fabric (Table 12).

Structure	The distribution of floats across the fabric
Yarn	The physical component of the fabric
Sett	The density of warp ends and weft threads in the cloth based on structure and yarn type

Table 12 Key variables in woven structures.

Using the basic grid as a foundation it is proposed that through the manipulation of the structure, yarn and sett the cloth can be used for the production of repeated patterns of movement by allowing pre-trained SMA wires to be accurately positioned during weaving and the creation of patterns of regularly placed alternatively trained wires.

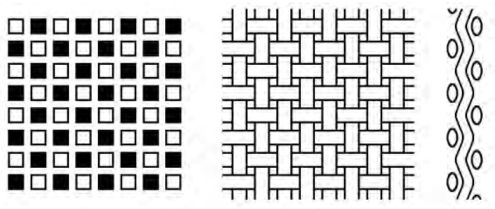
3.2.3 Selection of woven structures

The three basic woven structures, consisting of plain weave, twill weave and satin weave, can be combined and manipulated to form a diverse range of additional structures known as derivation or combination weaves. With the exception of techniques like leno, gauze and twinning which involve hand manipulation to change the order of the warp or weft threads, the woven structure maintains a parallel and perpendicular grid irrespective of the structure. Using this grid structure it is possible to order NiTi wires at even or specific intervals across the fabric. Although it is possible to integrate

NiTi in both the warp and weft, its use in the warp is wasteful as relatively large quantities will need to be discarded (and remain unusable) at either end of the warp as well as between samples (Chan Vili 2004). An additional factor that is pertinent to the use of NiTi in the warp is that during the weaving process the warp remains under tension which will reduce its conformity to the woven structure. As this investigation is concerned with the interfacial relationship of NiTi components and the supporting structure it will concentrate only on the integration of NiTi in the weft direction.

3.2.3.1 Plain weave

Plain weave (Figure 22) is the simplest and most important of the three basic woven structures and is used in about 80% of all woven fabrics (Tortora and Merkel 2007). When closely sett, plain weave produces a very strong, light, tight fabric that is the most secure of all woven structures. Plain weave can be created on two shafts producing a simple one under one over construction which maximizes the number of interlacements between the warp and weft threads and contains no floats. The tightness achievable in plain weave means it is likely to be suitable for holding the inserted SMA wires securely in place although when sett to produce a very tight structure the resulting stiff, crisp fabric can be unsuitable for being worn against the skin for long periods of time. Plain weave plays a major role in this investigation, and is explored throughout phases 2 and 3.



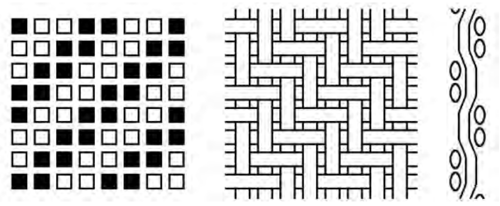
a. b. c. d.

a. Peg plan (showing shafts and picks)
b. Peg plan (basic)
c. Representation of interlacements
d. Cross sectional representation

Figure 22 Visualisations of the plain weave structure.

3.2.3.2 Twill weaves

Twill weave (Figure 23) is the second of the basic weaves, constructed with each end floating over or under at least two picks while the pattern moves over one end on each pick giving the characteristic diagonal rib or twill line. The smallest twill repeat can be seen in the 2/1 twill which can be created on three shafts and is constructed by each end crossing first two picks then one. The 2/2 twill is the smallest even sided twill and is one of the most popular weaves for men’s wear. 2/2 twill is constructed by each end successively passing over then under two picks to produce a strong durable fabric with a softer handle when compared to plain weave due to the reduction of interlacements. Although still a comparatively stable fabric the looser structure would allow greater movement of the SMA wire and reduce the transfer of energy from the wire to the structure, reducing accuracy of shape control. 2/2 twill plays a major role in this investigation, and is explored throughout phase 2 and 3.



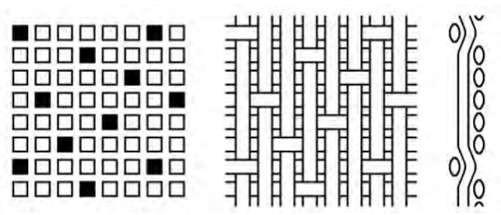
a. b. c. d.

e. Peg plan (showing shafts and picks)
f. Peg plan (basic)
g. Representation of interlacements
h. Cross sectional representation

Figure 23 Visualisations of the 2/2 twill structure.

3.2.3.3 Satin weaves

The third of the basic weave types is satin weave (Figure 24) which is characterised by the face of the fabric being dominated by either warp or weft floats. Differing from the diagonal patterning of twill weaves, satin weaves space the intersections as evenly and widely as possible in an attempt to disrupt any visual patterning. Common satin weaves use six, eight and twelve shafts with one repeat consisting of the weaving of each shaft once. Increasing the number of ends from the minimum of five, aids the visual dispersion of the intersections but increases the float length which in turn reduces the stability of the cloth. The result of having long floats with widely spaced intersections is that the fabric has a smooth surface which can be further accentuated by the use of smooth yarns like silk or filaments. The reduced number of interlacements increases the number of ends required when setting the fabric. Care must be taken when setting the fabric as an under set cloth will produce a spongy fabric with poor handle and durability whereas an over set cloth will produce ribbed effects. An alternative to maintaining long floats in a stable cloth is to *stitch* the floats into a fine but more stable backing weave to form a stitched double cloth. The structure of a satin weave would provide minimum resistance to the movements of an inserted NiTi wire and dramatically reduce the effective shape transfer from the inserted wires to the cloth. The satin woven structure is investigated in phase 3, study i.



a. b. c. d.

i. Peg plan (showing shafts and picks)
j. Peg plan (basic)
k. Representation of interlacements
l. Cross sectional representation

Figure 24 Visualisations of the 6 end satin weave structure.

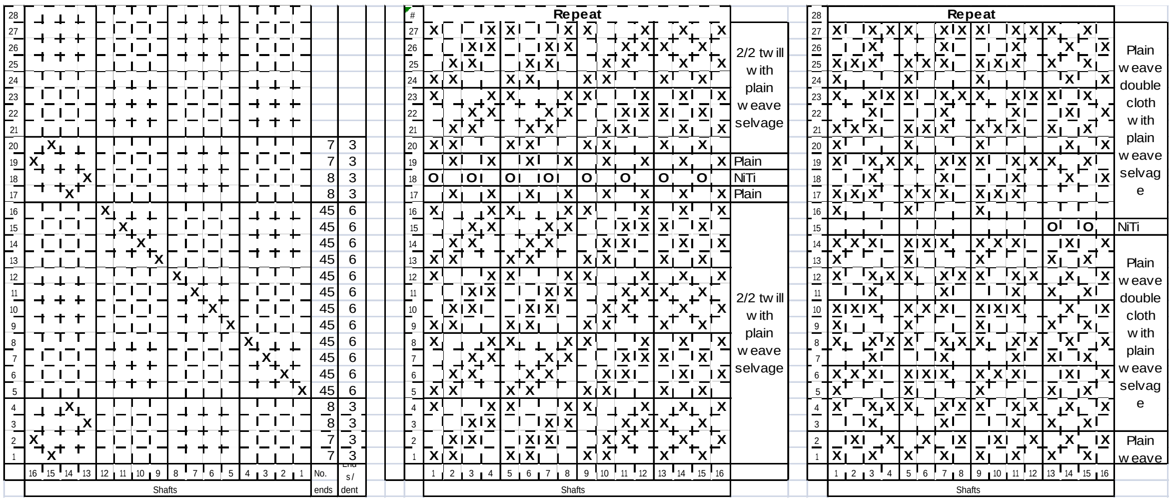
3.2.3.4 Combination weaves

The combining of different woven structures in a single fabric can be used to alter its control and mechanical characteristics, facilitating different tactile and functional properties. Manipulation of the supporting structures either parallel or perpendicular to the inserted NiTi component can facilitate and alter the shape transfer from the NiTi component to the fabric, promoting either a direct shape transfer or a variety of different levels of secondary shape transfer.

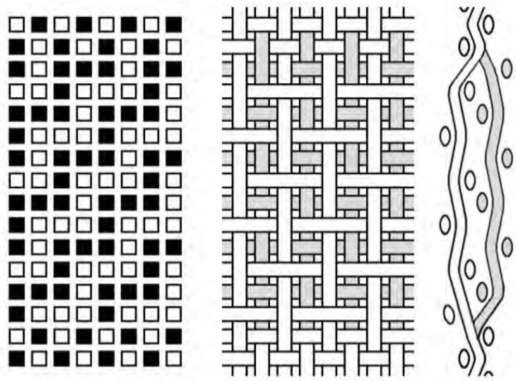
2/2 twill with plain weave sections running parallel to inserted components

The first combined woven structure used in this study alternates between 2/2 twill and plain weave in succession running parallel to the inserted wire as the fabric is woven (Figure 25). This combination maintains an even transfer of force down the length of the wire to the textile allowing for a tighter plain weave to be woven in the picks directly surrounding an inserted wire while the majority of the cloth can utilise a 2/2 twill with a softer handle and more visually appealing qualities. To ascertain whether this configuration of plain weave and 2/2 twill has any mechanical benefit over straight insertion into a 2/2 twill, comparative evaluations were conducted in phases 2 and 3.

The design of a suitable transition between these woven structures and the positioning of the floats is investigated in Figure 25 a. - e. The transition between structures is crucial for the production of a stable structure that will increase the support of the NiTi rather than lose integrity. As well as the mechanical impact of the transition between woven structures the visual impact was also considered. If floats greater than 2 picks were present on the face of the fabric they would give an uneven and irregular look to the cloth.



a. b. c.



d. e. f.

m. Draft for pick plans (b) and (c)
n. Peg plan (the cloth is predominantly 2/2 twill with plain weave selvedge but with three picks of plain weave surrounding a fully integrated NiTi wire)
o. Peg plan (the cloth is predominantly 2/2 twill with plain weave selvedge but with three picks of plain weave surrounding a fully integrated NiTi wire)
p. Peg plan of double cloth pocket (basic)
q. Representation of interlacements in a double cloth pocket
r. Cross sectional representation of double cloth pocket

Figure 25 Visualisations of a double cloth structure.

Using this second construction method, with the NiTi wire effectively externally mounted (not directly integrated in the structure along its full length) parallels can be drawn to the mechanism of ‘tilt force buckling’ investigated by Chaudhry and Rogers (1991) in section 2.5.2.3. In the semi-rigid structures investigated by Chaudhry and Rogers the externally mounted and offset SMA wire actuators provided greater movement and deflection than fully integrated wires due to the differential movement between the beam and actuator. A means of maximising this method of construction would be to secure a spiral trained NiTi wire in the selvedges at either side of a woven pocket. If the wire is in the deformable low temperature phase and is straightened out during insertion into the woven structure, upon activation the coils within the pocket will be able to reform contracting the fabric (Figure 26).

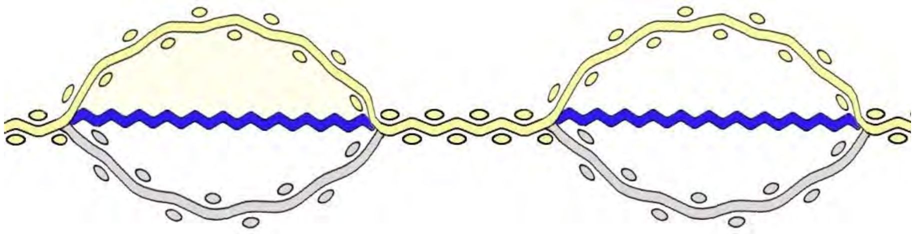


Figure 26 Visualisations of activated double cloth with integrated SMA wire (original in colour).

To add greater control to the cloth, wires of different lengths can be inserted at intervals to produce an accurate and controlled staggered contraction. The combination weaves described above and depicted in Figure 25 and Figure 26 are explored in phase 2, study ii and iii.

3.2.3.5 Summary of woven structure

The differing interfacial properties that can be achieved through the manipulation of a number of structural and material variables are 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 therefore 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.

3.2.4 Selection of yarn

Unlike the work of Chan (2003; 2004; 2007), who focused on the spinning of fancy yarns to soften the visual and tactile impact of the large 200µm and 300µm diameter wires (discussed further in section 3.2.6.1), this investigation will only look at the insertion of plain (un-spun) NiTi wire and ribbon into the woven structure. The rationale behind this is to maximise the accuracy and control of the inserted wire. If first incorporated into a yarn a less uniform interface exists between the SMA and woven structure. This increases the interfacial variables, affecting the transfer of control from the wire to the cloth, creating less predictable displacements.

The variables surrounding the choice of single component yarns to produce the supporting structure are numerous and as such offer the potential to select yarns with specific properties to facilitate or impede movement of an inserted NiTi wire as well as offering additional function. With the highly developed production and finishing methods now available to a yarn manufacturer an ever expanding range of physical and mechanical properties can be applied to the same basic yarn type. Figure 27 characterises some of the main variables and mechanical properties that different yarns can offer.

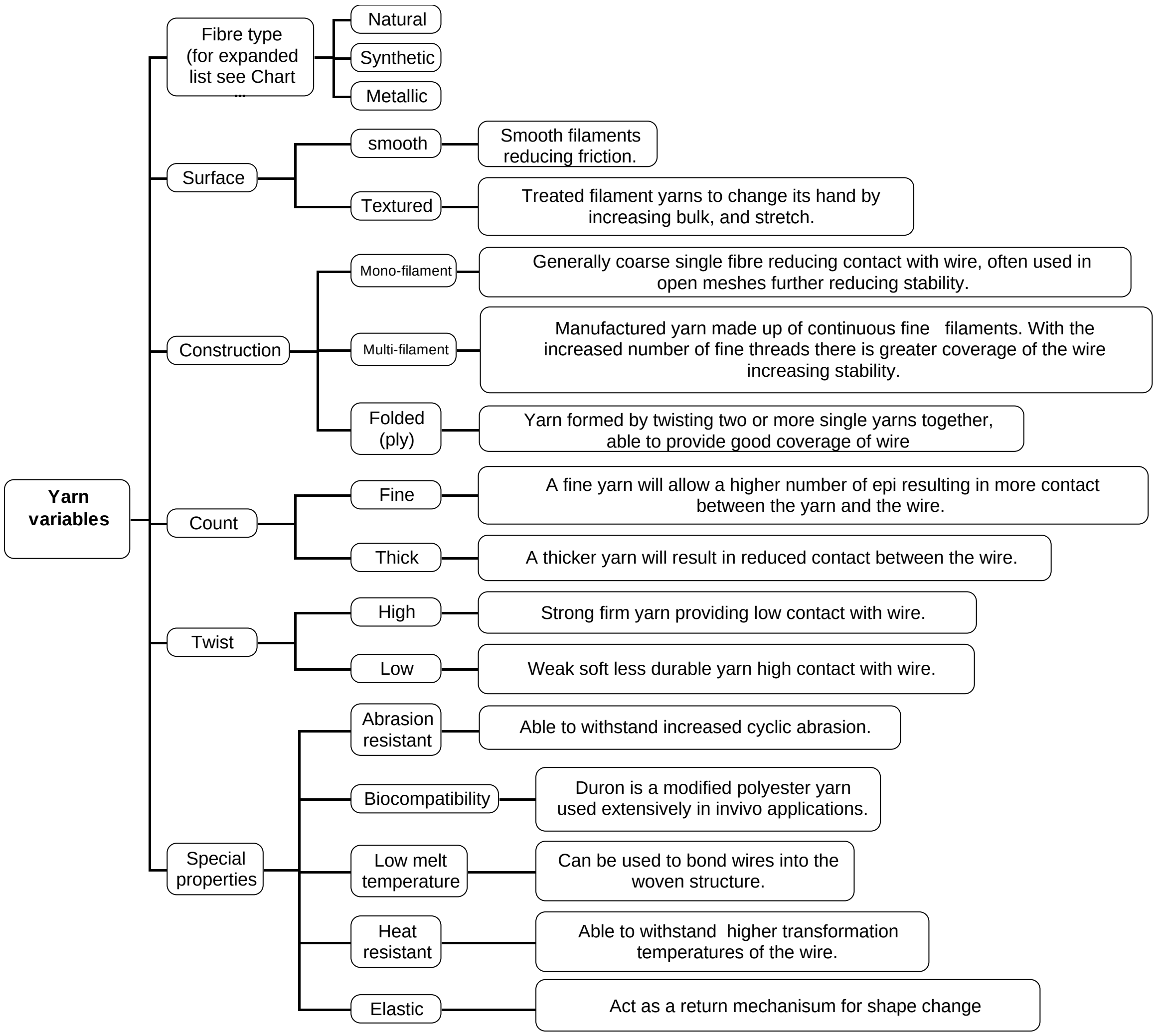


Figure 27 Key variables in the choice of yarn.

From the vast array of yarn types available on the market four were selected for evaluation as part of this investigation each offering very specific attributes for the integration and control of NiTi wire in woven structures. The four yarns selected are mercerised cotton, textured multifilament polyester, stretch broken Kevlar and un-textured multi filament Duron. Scanning electron microscopy (SEM) was used to investigate the differences in the fibre structure of the yarns used (Figure 28 and 32 – 34). To achieve a clearer SEM image of the fibres, the yarns were mounted in a relaxed and separated state and as such should not be used as a guide to their diameter. The SEM process is further described insection 2.2 in relationship to the surface structure and composition of the NiTi components.

3.2.4.1 Mercerised cotton

In spite of the rise in the production and use of synthetic fibres, cotton remains the second most frequently used fibre by the textile industry (Oerlikon 2009), particularly in the apparel markets. The process of mercerizing cotton was discovered in 1844 by John Mercer (Tortora and Merkel 2007) and involves the immersion, usually under tension, of cotton fibres, yarn or fabric in a sodium hydroxide solution followed by neutralisation in acid. The effect of this process on the cotton is a permanent swelling of the fibres (Figure 28) which visually increases their lustre and affinity with dyes, but also increases its tensile strength. The increase in fibre strength makes it a better choice than un-mercerised cotton for use as a supporting fibre for active textiles and for this reason a 2/40cc mercerised cotton supplied by Fairfield yarns was selected. Mercerised cotton yarn was used extensively in phases 2 and 3, and as a base line in all the evaluations.

a. b. c.

s. Image taken at 443 x magnification showing the 2 fold twisting of the yarn.
t. Image taken at 2.6k x magnification showing the swollen fibres resulting from mercerisation.
u. Image taken at 20k x magnification showing the smooth cylindrical surface of a mercerised cotton fibre.

Figure 28 SEM images of the 2/40cc mercerised cotton yarn used in phases 2 and 3.

3.2.4.2 Synthetic fibres

The first man-made synthetic polymer fibres were spun from chlorinated polyvinyl chloride (cPVC) and commercially produced in Germany in 1936. Although this had little commercial value as a textile fibre the production of Nylon (polyamide) in 1939 and Polyester under the ICI trade name Terylene® in 1941 were widely adopted by the apparel industry. These man-made fibres heralded a breakthrough that allowed technologists to manipulate and control the construction and production on a micro-scale. A common problem with early synthetic fibres was their inability to absorb moisture. This resulted in a harsh, uncomfortable fabric that tended to either build up a static charge or hold condensation. As a result of engineering, the properties of polyamide and polyester micro-fibres commonly known under the DuPont brand names Tactel® and Coolmax® respectively have revolutionised the active sports-wear market, producing fabrics that are soft to the touch and quick drying due to their ability to wick moisture away from the skin so that it can evaporate quickly (Hu 2004). As well as moisture management a myriad of other properties have been developed that often out-perform traditional natural fibres resulting in many synthetic fibres being used in novel applications.

Three distinct synthetic fibre types were selected for evaluation based on their specific attributes. These were polyester, Kevlar and Duron.

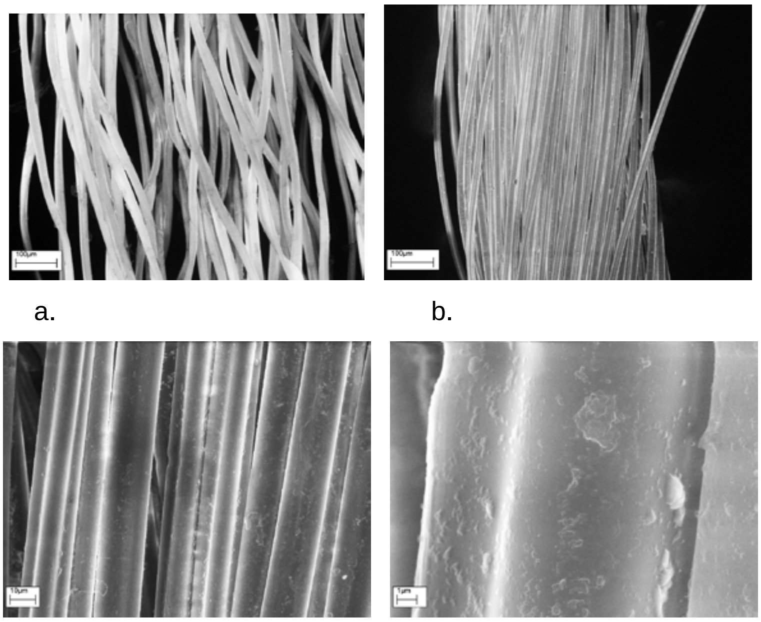
3.2.4.3 Polyester

Polyester, whether in staple or filament form, is the most widely produced of the synthetic fibres and is used in applications as diverse as apparel, household, industrial, geo and medical textiles. Polyester fibres demonstrate high strength and abrasion resistant properties and can be used in all forms of textile construction demonstrating great versatility and adaptability to process. Polyester fibres blend well with other fibres and can be modified, altering its aesthetic and tactile qualities. Specific characteristics that have made polyester an attractive fibre for use in apparel applications are its minimal care attributes, being crease resistant, quick drying, and demonstrating good shape retention after successive wear and cleaning cycles. With the development of the fibre structure and composition, other attributes can be heightened including increased chemical and heat resistance.

As well as its extensive use in apparel application, a major reason for the selection and evaluation of polyester is its use as an *in vivo* medical textile. Due to its strength and relative biocompatibility, polyester has been used as a suturing material and for implants like the CorCap™ cardiac support device, and as support devices for reconstructive surgery. A specific medical application that is of interest is the cardio vascular graft stent developed by Anson Medical (Anson Medical 2009) (Figure 29). Using catheter insertion techniques this device is deployed to support a weakened cardio vascular artery. The current design for the stent involves the attachment of pre-trained superelastic NiTi wire, to the surface of a Dacron microfiber tube using computer controlled embroidery techniques. The direct integration of the NiTi wire into the woven structure could have a number of benefits including a reduced and smoother profile which could aid insertion and also promote less disruption to blood flow through the device.

Figure 29 Cardio vascular graft stent (Anson Medical 2009) (original in colour).

The polyester yarn chosen for use in this investigation is a textured 35 tex multi-filament yarn supplied by American & Efird Ltd (Figure 30). The choice of this yarn was to produce a comparable weight cloth to the mercerised cotton. The texturisation of the yarn improves the bulk and elasticity giving the cloth a less harsh and improved hand that is closer to cotton. The polyester yarn was used in phase 2, study i, and phase 3, studies ii and iii.



a. b.

c. d.

v. Image taken at 600 x magnification showing the filaments and texturisation of the yarn
w. Image taken at 443 x magnification showing the filaments of the yarn (under light tension)
x. Image taken at 2.6k x magnification (under light tension)
y. Image taken at 20k x magnification (under light tension)

Figure 30 SEM images of the 35tex textured polyester multifilament yarn used in phases 2 and 3.

3.2.4.4 Kevlar

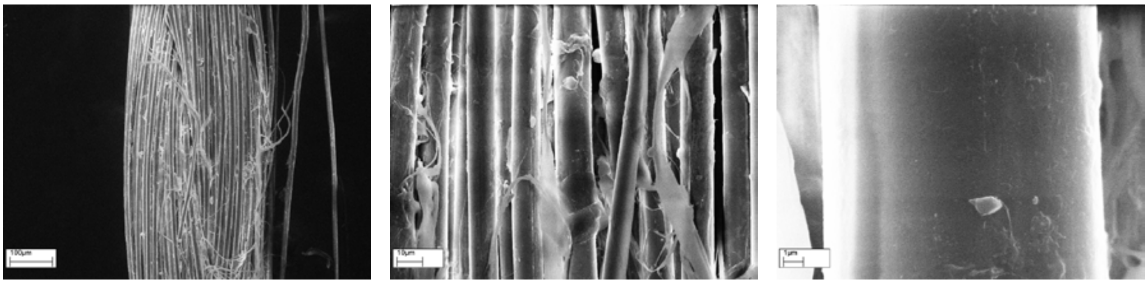
Kevlar was developed in 1965 by DuPont for space applications, finding its first commercial success in 1970 as a replacement for steel in racing car tyres. Aramid fibres like DuPont's Kevlar® and Invista's Cordura® have high tensile strengths being five times stronger than steel for an equivalent mass (Table 13), but at only one fifth the weight (Adanur 1995). High strength Kevlar also demonstrates outstanding stiffness, vibration dampening, impact resistances and has a high resistance to cutting, abrasion, chemicals, heat and ignition. These properties have made Kevlar an important fibre for specialist applications where strength and wear resistance is required. Applications include protective apparel like anti-stab vests and ballistics protection, sewing threads, strengthening fibres in composite structures for aircraft, boats and high performance cars, ropes, sails and sports equipment.

The choice of Kevlar as one of the yarn types to be evaluated was based on its high strength, stiffness, and abrasion resistance which would provide a stable supporting structure for the integration of the NiTi wire. An additional characteristic that makes the choice of Kevlar attractive is its heat resistant properties with a continuous working temperature of 230ºC and a short term use temperature of 315ºC to 370ºC. Although still unable to withstand the 400ºc to 500ºC required for the training of the NiTi wires, it is more than adequate for the 100ºC to 120ºC needed for the activation of high temperature thermal NiTi wires.

	Yield strength (MPa)	Tensile strength (MPa)	Density (g/cm^3)
Kevlar	3620	2757	1.4
ASTM A514 high strength steel	690	60	7.8

Table 13 Comparison of tensile strength and density of Kevlar and A514 steel

The Kevlar yarn chosen for the evaluations is a type R, 80/2Nm, stretch broken yarn supplied by Schoeller GmbH (Figure 31). Although slightly finer than the mercerised cotton the 80/2Nm yarn would produce a similar weight cloth. The choice of a stretch broken 2 fold Kevlar yarn provides more comparable characteristics to the mercerised cotton being used as it is less harsh than a filament yarn and subsequently gives the cloth an improved hand. The Kevlar yarn was used in phase 3, studies ii and iii.



a. b. c.

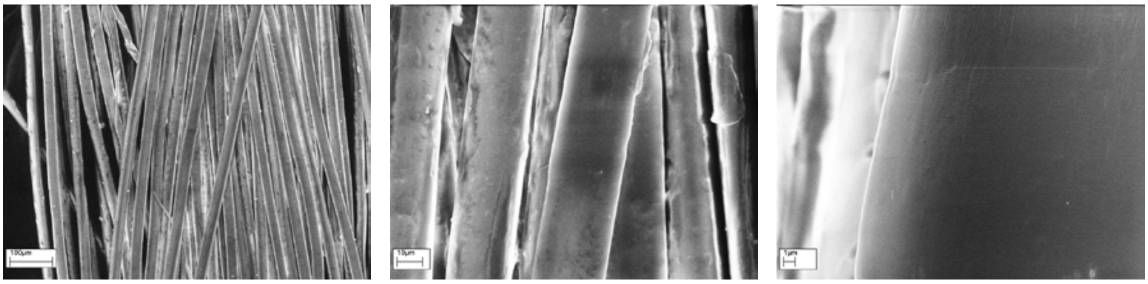
z. Image taken at 443 x magnification showing the 2 fold twisting of the yarn
aa. Image taken at 2.6k x magnification
bb. Image taken at 20k x magnification

Figure 31 SEM images of the 80/2Nm stretch broken Kevlar yarn used in phases 3.

3.2.4.5 Polypropylene

Polypropylene (PP) was developed in 1951 at Hoechst AG. Propylene, the main component of polypropylene, was produced in abundance and initially considered of little value being a by-product of petrol (Adanur 1995). Polypropylene is light weight, has good strength and elastic recovery whether wet or dry, as well as demonstrating good abrasion, fatigue and electrical resistance, remaining supple after melting, low moisture absorption and good wicking properties. It demonstrates good biocompatibility and is used in the treatment of hernias as patches below the skin. Other common applications include the production of ropes, sewing threads, upholstery and as a base layer in cold weather environments and underneath body armour. Although under normal conditions PP has excellent mechanical properties it has very poor thermal stability with maximum processing temperatures of 125ºc to 130ºc while still maintaining fibre integrity and a melting point of 165ºc. This low thermal stability coupled with its retention of suppleness suppelty after melting and low flammability has resulted in polypropylene being used for laminating and melt coating.

The polypropylene yarn chosen for this evaluation was 300/72 Denier multifilament Duron CL supplied by Plasticisers Ltd (Figure 32). The choice of this PP yarn was made because it would produce a similar weight cloth to the cotton but this was secondary to its ability to be melted and form an encapsulating support for the NiTi wire. The encapsulation would secure the NiTi wire in the structure and due to the conformity of the material minimise the loss of transferred force from the NiTi to the fabric. The electrical resistance properties could also be used in future applications if the wire required electrical resistive heating. All the polypropylene samples underwent a heat treatment before testing which is further discussed in section 3.2.8.3. The Duron yarn was used in phase 3, studies i, ii and iii.



a. b. c.

cc. Image taken at 443 x magnification showing the filaments of the yarn
dd. Image taken at 2.6k x magnification
ee. Image taken at 20k x magnification

Figure 32 SEM images of the 300/72 Denier multifilament Duron CL used in phases 2 and 3.

The samples produced for the other fibre types all consisted of a single yarn type. Although this is also the case for the Duron samples, additional samples were produced and tested which combined Duron with the mercerised cotton in various warp and weft configurations.

Threading of a combined cotton and Duron warp (used in phase 3, studies ii and iii)

The production of samples with an evenly mixed cotton and PP warp offered an intermediary comparison to pure cotton and PP samples. These samples were woven in plain weave and 2/2 twill. The use of a straight alternate threading plan would provide a poor placement of warp yarns along the integrated component. Figure 33 (a) demonstrates that if an alternate pattern of threading is used when the component is inserted, yarn 1 will be on the back of the cloth and yarn 2 on the face. To achieve an even and alternate distribution of warp yarns 1 and 2 across both sides of the inserted component the warp was threaded in alternate pairs, as in Figure 33 (b) and (d). An alternate crossing of the inserted component can be seen. Having the yarns crossing alternately will better encapsulate the inserted element increasing the effective bond after heat setting. For the 2/2 twill (Figure 33 c and d) the alternating of yarn 1 and 2 across the inserted element occurs whether an alternate or paired threading plan is used.

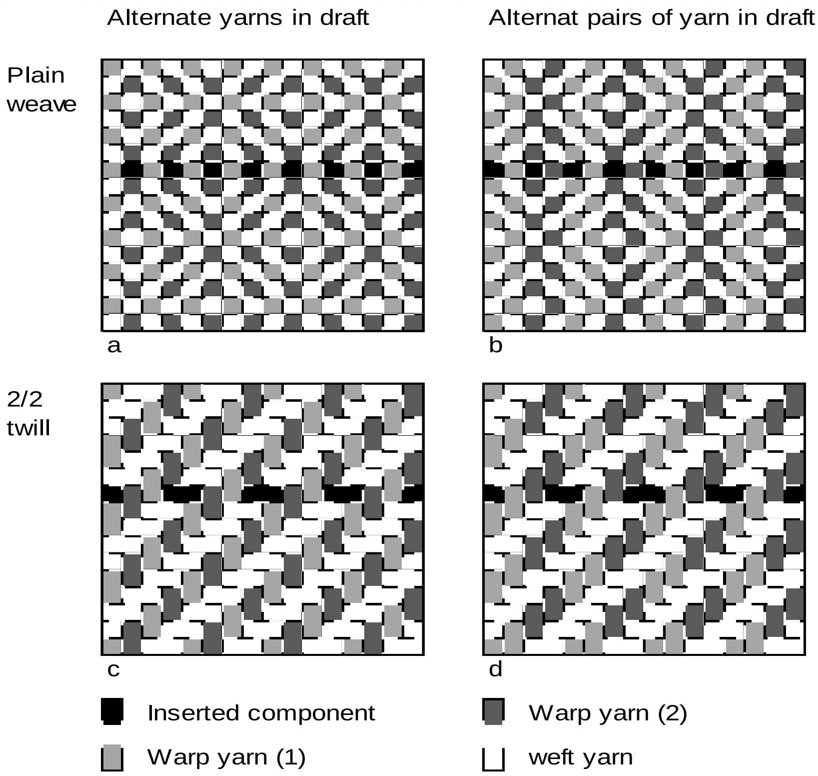


Figure 33 Trial threading plans for mixed yarn, plain weave and 2/2 twill warps.

3.2.4.6 Tensile testing of yarns

Tensile testing was carried out using an Instron computer controlled tensile tester to acquire the limits of the yarns used in the supporting structures of the samples (Table 14). This included an un-heated set Duron yarn which although it was not used in this condition demonstrated the breaking pattern of a continuous multi filament yarn. The results acquired from these tests would provide a level on which to evaluate the effectiveness of the integration of NiTi components into the woven structure.

Extracted yarn	Supporting yarns	Loading to breaking point (g)	Breaking strain (N)
Cotton	Cotton warp and weft Duron warp and weft Duron and cotton warp, cotton weft	10,882	106.6
Kevlar	Kevlar warp and weft	16301	159.80
Polyester	Polyester warp and weft	6911	67.75
Polypropylene (un-heated set)	All samples contained heat set polypropylene yarn when tested.	8698	85.27

Table 14 Extension to breaking point for yarns used in the samples.

Figure 34 shows the patterns of breaking seen in the samples tested. Each of the yarn types demonstrated particular characteristics relating to the composition of the yarn and its production method. The cotton, Kevlar and polyester yarn were all spun yarns whereas the polypropylene yarn was a continuous filament. As well as achieving the highest loading before failure the Kevlar yarn did not show any loss of integrity until the point of maximum loading, upon which total failure was seen. This was in contrast to the other yarns which all demonstrated a slow degradation to the integrity of the yarn during loading. On reaching the point of maximum load the cotton and polyester spun yarns demonstrated total failure in a similar manner to the Kevlar yarn. Instead of the dramatic failure seen in the spun yarns the polypropylene yarn showed a slow degradation of continuity after the point of maximum loading as individual filaments failed.

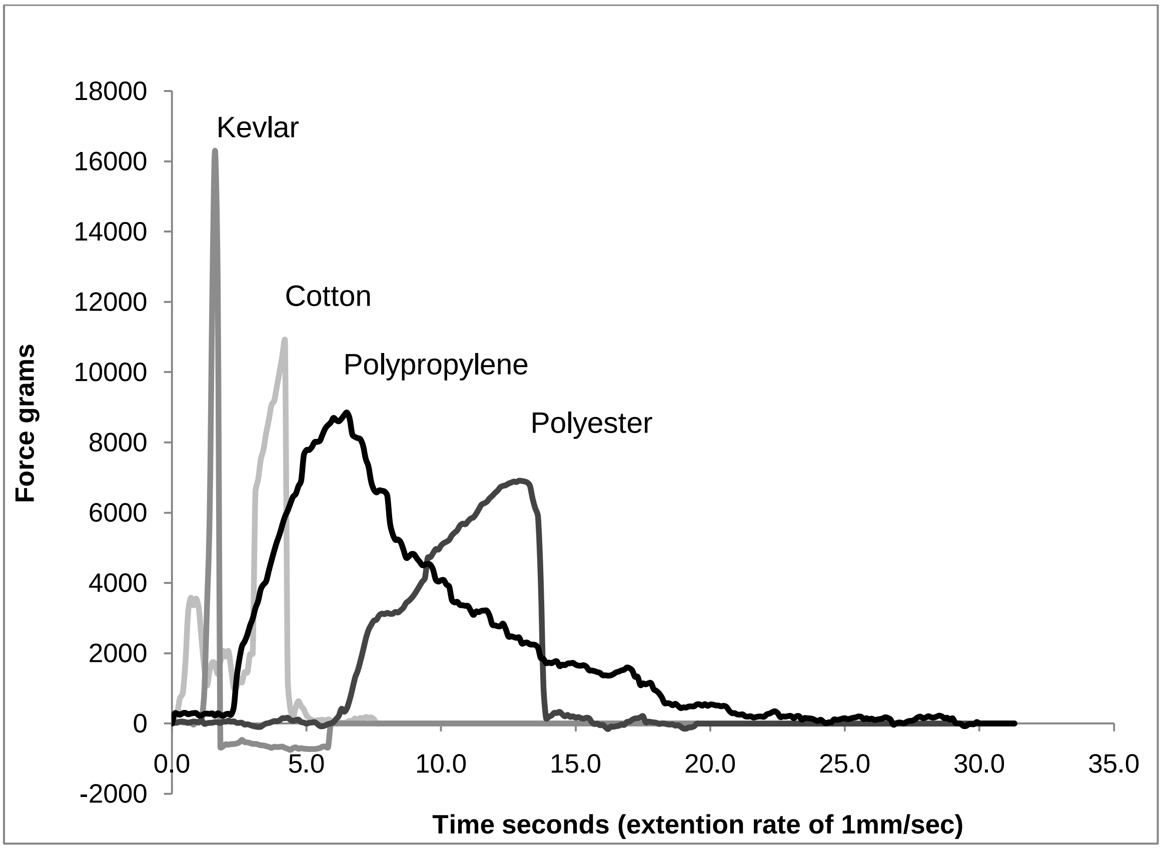


Figure 34 Maximum loading for yarns (tested to failure).

3.2.4.7 Metallic fibres

Single component metallic fibres

Dating back over 3,000 years, metals have had a long history of being integrated into textile structures or applied as embellishments after construction. Early metallic threads were produced by beating metals like gold, silver, bronze and copper into thin sheets before slitting into fine ribbon. This method produced ribbons that were not very flexible and would often have abrasive edges that were uncomfortable to the wearer and caused damage to the supporting fibres. A later method that is still in use today, produces stronger, more even and less abrasive wires and ribbons is the drawing down of rods through successively smaller apertures until the wire reaches the required size and cross section (Cook 2005). As a result of these improvements in technology finer wires can now be produced with diameters as small as 4µm - 8µm (Adanur 1995; Cook 2005) that are more compatible with traditional textile fibres.

One of the main compatibility issues with the integration of any wire into a very flexible and adaptable structure, such as textiles, is the issue of minimum bend radius. When metallic wires and most monofilament yarns exceed their minimum bend radius they are liable to buckling and subsequently the permanent creasing of the component. Table 10 shows the minimum bend radiuses recommended for Flexinol NiTi thermal shape memory wires in a range of diameters. It can be seen from this chart that as the diameter of the wire decreases so does the minimum bend radius. Whether as staple fibres or continuous filaments, most conventional textile yarns are made up of a number of very fine fibres spun together for strength. The combination of the fineness of the fibres and the spinning results in yarns that can be bent back on themselves or even knotted without detriment to the fibre.

With the reduction in wire diameter the finer wires can now be cut into shorter staple fibres and then spun to form 100% metallic yarns that are more flexible than a monofilament wires and have a much softer handle. In 2000 Reiko Sudo and Nuno produced a fabric woven from 100% spun stainless steel yarn with a fibre diameter of 8µm. The resulting fabric is counter intuitive, being visually recognisable as a metallic fabric but with a very soft and supple handle akin to that of traditional fibres (Braddock and Mahony 2005; Sudo and Nuno corporation 2005). In their 100% metallic state these yarns possess the same properties as the original metal / alloy resulting in very durable and tear resistant textiles that are able to withstand high temperatures. The Nuno fabrics were coloured by heating with a gas flame to produce iridescent colouration and patterning. In blended yarns the inclusion of metallic fibres aids the heat resistance of the other fibres due to their ability to transfer heat and disperse it across the whole surface of the textiles.

Multi component metallic fibres

Multi component metallic fibres are varied in their composition but are predominantly produced by one of two methods. The most common method was developed in 1950 under the trade name Lurex®. This is produced by sandwiching a thin metallic foil, usually aluminium, between layers of polyester to produce a yarn. The polyester film serves to strengthen the foil, that on its own would be too fragile, as well as preventing the foil from tarnishing and irritating the skin. The resulting sheets can be between 0.889 µm and 3 µm in thickness and are then slit into fine strips of between 3.2 and 0.2 mm. For increased visual appeal the polyester coatings can be coloured. Another method used is to coat a plastic film with vaporised aluminium which is then sealed between further layers of plastic or coated with a polymer lacquer. These fibres are used extensively as decoration in both woven and knitted textiles.

3.2.5 Summary and comparison of yarn counts and setting of cloth

Once the yarn types had been selected their specific characteristics needed to be considered. The acquisition of such varied yarns with similar physical dimensions is very problematic given the number of variables, such as linear density, yarn density, and the packing factor of the yarn. The packing factor depends on a range of additional variables which are shown in Table 15.

Parameters influencing the packing factor	Variables
Fibre	Crimp Length Size (diameter) Cross section shape
Yarn	Twist Spinning method
Fabric	Sett (warp and weft densities) Weave

Table 15 Parameters and variables influencing the packing factor.

Using the equation provided by Seyam (2002) these parameters are considered and used in the calculation of yarn diameter (Equation 1) and subsequently to calculate the sett of the cloth.

$$d = \frac{1}{280} \times \sqrt{\frac{Nt}{\Phi \rho f}}$$

d	yarn diameter(cm)
Nt	yarn linier density (tex, i.e.g/km)
Φ	yarn packing factor (= ρy / ρf)
ρf	fibre density (g/cm³) (=Φ x ρy)
ρy	yarn density (g/cm³)(=Φ x ρf)

Equation 1 Calculation of yarn diameter in cm from the tex yarn count system.

To calculate the yarn's diameter first the individual yarn counts were converted to the tex yarn count system from which they could be converted using Equation 1 into µm yarn diameters. It should be noted that due to the relaxed manner in which the yarn samples were mounted the SEM images should not be used as a guide to yarn diameter.

	Purchased count	Tex count equivalent (g/km)	Diameter µm	Construction
Mercerised cotton	2/40cc	30tex	203µm	Two fold yarn
Polyester	35tex	35tex	222µm	Textured multifilament
Kevlar	80/2Nm	25tex	192µm	Two fold yarn
Duron	300/72den	33tex	258µm	Multi filament

Table 16 Yarn types and dimensions used in the investigation.

The difficulties faced in the selection of comparable yarn counts are highlighted with the Duron yarn which, using the tex system, has the second highest count after polyester, but in contrast when the yarn diameter is calculated, taking into account fibre density and the packing factor, Duron yarn has the largest yarn diameter. These inconsistencies are a result of the smooth multifilament nature of the Duron coupled with its low density at 0.91g/cm³ compared to 1.38g/cm³ for polyester, 1.52g/cm³ for cotton and 1.44 g/cm³ for Kevlar.

3.2.5.1 Sett

The inherent properties of textile structures have meant that they are not easily described in mathematical forms based on geometry due to the physical variations of the yarns and their construction methods. Since 1930 when Peirce published the first paper on theoretical research concerned with the mechanics of textiles (Peirce 1930) many different geometric forms have been investigated for the modelling of textiles structures. The focus for better understanding has been the theory of maximum weavability which is concerned with the prediction of the handle of a fabric based on the end per inch and therefore the maximum sett for any given yarn or weave structure. The need to predict the maximum sett and handle of a fabric were driven by factors of cost, whether in saving time by not designing un-weavable fabric or by preventing damage to machinery and the breaking of ends that slows production. With the increase of automation and pressures from within the industry and consumers to remain competitive, companies now rarely hold large stocks of materials and are relying more and more on the 'just-in-time principle'. This change in manufacturing style has resulted in the need to be able to understand and predict the quality and handle of a fabric and attain the correct results first time. The ability to communicate these properties reliably internationally across different languages and to different points in the supply chain has become more important than ever.

The manipulation of the sett of a woven structure will play an important role in the dynamics of the SMA and the resulting fabric. From the many setting theories that have been developed which look at different aspects of cloth production the decision was made to use Brierley's 'Theory of empirical maximum weavability' (Equation 2). This is based on a number of factors. Brierley's theory takes into account a wide number of variables as it can be applied to any type of yarn, fibre or woven structure. Unlike other setting theories which often just use the linear density of the yarn in the calculation, Brierley uses a separate equation (Equation 1) to calculate yarn diameter.

This equation takes into account density of a yarn, fibre density and linear density and therefore differentiates between fibre types and yarn production techniques. In the actual setting equation the diameter of the yarn is combined with the weave factor which is the relationship between warp end and intersections in one repeat, as well as a constant for the weave type which allows for the length of floats in the weave.

$$T = \frac{F^m}{1.84 \times D}$$

T Ends per inch
D Yarn Diameter
m Constant for weave type
F Weave Factor = (W / I)
W Threads in one repeat of the weave
I Intersection in one repeat of the weave

Equation 2 Brierley's theory of empirical maximum weavability.

Demonstrating the variety of fabrics that can be produced by simply altering the sett, yarn weight and finishing can be seen in a cotton plain weave fabric with the production of muslin, organza, duck and Ottoman fabrics. Using Brierley's theory of empirical maximum weavability, calculations were made for the sett of samples to be produced in phases 2 and 3 (Table 17).

Yarn	Yarn count	Yarn Ø µm*	epi†	Plain weave % sett	2/2 Twill % sett	6 end satin % sett	Phase 2			Phase 3		
							S i	S ii	S iii	S i	S ii	S iii
Mercerised cotton	2/60cc	166	84	101	77		X					
	2/40cc	203	67	98							X	X
			72	106	80	67			X	X		
			88		99						X	X
			96	141						X		
			120	176	135		X					
			144	212		133		X	X			
			168	247	189		X					
Mercerised cotton with Duron weft	2/40cc 300dtex	229	60	100						X		
			78		99					X		
Kevlar	80/2Nm	192	72	100							X	X
			96		102						X	X
Polyester	35tex	223	60	97							X	X
			80		99						X	X
	40tex	238	112	201			X					
Duron CL	300dtex	254	54	99							X	X
			72		101						X	X
Duron warp with cotton weft	300dtex 2/40cc	229	60	100							X	X
			78		99						X	X
Cotton & Duron warp Duron weft	300dtex 2/40cc	220	63	100							X	X
			81		99						X	X

*Calculated using Equation 1 Calculation of yarn diameter in cm from the tex yarn count system.
†Calculated using Brierley's theory of empirical maximum weavability Equation 2.

Table 17 Overview of yarns, epi and weave structures used in phase 2 (P2) and Phase 3 (P3).

3.2.6 Selection of NiTi properties

As discussed in section 2.6.3 there has been limited published research investigating the properties of an inserted NiTi wire into a woven structure. As a result there are no clear guidelines for the optimisation of the available properties. Following a review of the available literature three physical characteristics were identified as being fundamental in affecting the interfacial relationship and performance of an inserted NiTi wire. These characteristics are the cross-sectional dimension of the wires, cross-sectional shape, and surface finish. An additional two characteristics were identified which are based on the training of the NiTi wire and these are the method of training and the shape the trained form would take. These last two characteristics are associated with the form the transferred shape would take rather than the interaction between the wire and textile. The reliance of this study on stock wires held by suppliers due to the relatively small quantities required (100m) made it difficult to obtain specific combinations of properties. The following section investigates the three main characteristics that are important for the transfer of form from the trained NiTi wire to the textile, followed by a discussion on the properties focused upon for this investigation.

3.2.6.1 Dimensions

Due to the limited available data relating to the integration of NiTi wires into woven structures the review of NiTi was extended to include investigations into unidirectional fibre reinforced rigid composites and also flexible silicone NiTi composites, as parallels can be made between the construction methods. With the exception of Foreman et al. (Foreman, Nensi et al. 2007) who used rectangular section wire ribbon, previous investigations have focused on round cross sections. It was also noted that there was a general consensus on the dimensions of the wire (Table 18) at around 125µm - 200µm with the exceptions being Chan (2004) using 300µm and 200µm wire and Choi and Lee (1998) who used a 380µm wire. The choice of wires with a diameter of around 150µm demonstrates a good combination of diameter and efficiency for integration into woven textiles (Boussu, Bailleul et al. 2002).

An additional factor in the selection of wire diameter is the NiTi volume fraction which relates to the percentage of NiTi wire in the final material. As part of the ADAPT Project (Barrett and Gross 1996; Balta, Michaud et al. 2000; Parlinska, Balta et al. 2000) it was noted that with a reduction in the NiTi diameter there was a corresponding reduction in the shape memory effect. To balance this reduction it was proposed that a corresponding increase in the NiTi volume fraction would re-establish the shape memory effect. In an investigation of epoxy composites Simpson and Boller demonstrated that a 150µm wire inserted at intervals of 2mm could be integrated into a composite structure avoiding the creation of air pockets in the resin around the wire thus producing a good quality SMA composite (Simpson and Boller 2008). The reduction in wire size is favourable when investigating the integration into textile structures as finer wires are more compatible with the woven structure and will reduce the stiffness and distortion of the cloth. As discussed in section 2.5.2.2the increase in the NiTi volume fraction in epoxy or silicone composites resulted in failure of the composite structure due to interfacial stresses between the composite and NiTi wire caused by repeated cycling. It is anticipated that integrating NiTi wire in a woven rather than a unidirectional fibre structure, will reduce fatigue due to its ability to disperse local stresses more evenly than other composite. An additional benefit of reducing the SMA size is a decrease in cyclic time due to the reduced mass of a single wire allowing quicker resistive heating and cooling, combined with a proportional increase in the total surface area of the wires allowing quicker convection cooling.

	Reference		Matrix	Wire µmØ	Wire spacing per /cm	Wire intervals mm	SMA Volume fraction %	Application
Non-woven unidirectional fibre composites	(M.Parlinska, Clech et al. 2000)	Part of the ADAPT Project funded by the European Commission	LTM212 epoxy Kevlar 29	150	5, 10, 20	2, 1, 0.5	11.8%	Vibration dampening
	(Parlinska, Balta et al. 2000)		LTM217 epoxy Kevlar 29	150	4, 8, 16 5, 10, 20	2, 1, 0.5	11.8%	Vibration dampening
	(Stalmans, Tsoi et al. 2000)		Epoxy Kevlar 29	150	Undisclosed	Undisclosed	11.8%	Vibration dampening
	(Choi and Lee 1998)		Epoxy Glass	380	Undisclosed	4	2.78%	Shape control
	(Barrett and Gross 1996)		Silicone	Undisclosed	Undisclosed	Undisclosed	Undisclosed	Artificial muscle
Woven composites	(Boussu, Bailleul et al. 2002)		Stainless steel	125 and 150	2.5	4	Undisclosed	Vibration dampening
	(Chan Vili 2004)		Various NiTi composite yarns	200 and 300	5, 9, 11,13,19			Visual manipulation of interior textiles
	(Foreman, Nensi et al. 2007)		Carbon fibre	Ribbon dimensions undisclosed	Undisclosed	Undisclosed	3% - 6%	Impact resistance

Table 18 Comparison of NiTi wires used in available literature.

3.2.6.2 Cross section

Metallic wires like monofilament yarns have a greater stiffness compared to spun yarns. Although super fine stainless steel fibres with a diameter of 4µm - 25µm have been spun into single component yarns, to date this has not been achieved with NiTi wires and will therefore not be discussed further here. As can be seen in the literature, from the few published works that investigate the integration of NiTi wire into either a yarn or directly into a woven textile the focus has predominantly been on the insertion of round section wires. The exception to this is Foreman, Nensi et al. (2007) who used a NiTi ribbon in the weaving of a carbon fibre NiTi composite. Although carbon fibres are themselves round in cross section to reduce the material thickness of a composite the carbon fibres are often laid down like tapes. This method of construction is more conducive to the integration of a ribbon than a round wire. The use of NiTi ribbons in a non textile composite has been investigated in a study by Jonnalagassa et al. (1998). This study was concerned with the transformation of NiTi ribbons in an epoxy matrix and the interfacial relationship between the two materials and looked specifically at de-bonding.

When considering suitable cross sections of NiTi for integrating into textile structures both ribbons and wire have advantages and any decisions will ultimately be dictated by the form of shape transformation and functional requirements of the application. Round wires have greater multi directional flexure when compared to ribbon due to the ribbon's enlarged cross section in one direction which could cause buckling if placed under lateral stress. For the accurate placement of a pre-trained NiTi wire there are distinct advantages in using a ribbon over a round wire. A greater level of accuracy can be achieved when inserting a ribbon due to the ability to orientate it within the structure. This can be further enhanced by marking the wire during training so that specific points can be aligned with the textile structure. An additional advantage of using a wire ribbon is its larger surface area to thickness ratio which, by decreasing the cooling time after activation, increases the cyclic speed while maintaining the handle of the fabric. In a robotic finger setup, a 20% increase in the speed of the finger's cyclic motion was seen when a round wire was replaced by a ribbon (Ohkata and Suzuki 1999).

3.2.6.3 Surface finish

Many surface treatments can be applied to NiTi alloys (Table 19) to improve the mechanical properties as well as biocompatibility of the wire. After heat treatment in an oxidizing environment NiTi alloys produce a titanium oxide finish (TiO_2) with smaller amounts of metallic nickel and nickel oxides (NiO and Ni_2O_3) (Shabalovskaya 1996). The natural oxide layers can vary from 2 – 20nm and range from a straw-like colour to blue. If the processing oxide layer is not removed before heating a black oxide layer may appear (Wu 2001), indicating a thicker layer, induced by accelerated film growth at elevated temperatures.

Brown / amber oxide	A very hard, smooth / slippery, oxide layer of between 50 and 300 nanometres thick and demonstrates good adherence properties.
Shiny black oxide	A thicker oxide layer above 400 nanometres thick. The oxide layer is also very hard and smooth and although adherence is good there is a greater possibility of flaking or spalling when compared to the brown / amber oxide layer.
Pickled / etched	A matte grey with no visible oxides although due to the aggressive oxide formation of titanium a thin, invisible oxide layer is formed that is several nanometres thick. As a result of the removal of the visible oxides a microscopic surface relief is left.

Table 19 Standard surface conditions of commercially available NiTi wires and ribbons.

A number of subsequent mechanical and chemical finishing processes can be used for the maximisation of specific properties and are here shown in Table 20.

Mechanical polishing	Leaving a bright silver surface that has been mechanically stripped of oxides.
Ultra fine polishing	Similar to mechanical polishing but leaving a mirror finish.
Centreless ground	Ground in such a way as to give very tight diameter tolerances and leaving the surface with small circular striations.
Electro-polishing	Removal of peaks from the surface, resulting in a smoother more uniform finish by means of an electro-chemical process.
Chemical polishing	Chemical process resulting in a bright, smooth finish.
Slurry blasting	Circulation of abrasive material through tubing to remove the as drawn texture from the inside diameter and can also be used to increase the inside diameters.
Micro blasting	Removal of oxides by means of passing high velocity abrasive material over the surface, resulting in a finely textured matt finish giving a good base for further processing.
Passivation	Creation of a titanium rich oxide layer improving the corrosion resistance of the surface, similar to anodizing aluminium.
PTFE coating	Encasing the wire in PTFE.
Other thin-thick film coating, e.g. plasma deposited, sputtered, electrodeposited	Various coatings for diffusion barriers, increased corrosion resistance, biological fictionalisation.

Table 20 Specialist mechanical and chemical finishes available for NiTi wire and ribbon.
The above information is compiled from (Memry 2002; Memory Metalle 2008; Johnson Matthey c2004).

In separate investigations two different surface types have been found to increase the adhesion of NiTi wires. Jonnalagadda Sottos et al. (1998) used sandblasted NiTi wire in order to maximize the adhesion between the wire and an epoxy matrix. In contrast, Simpson and Boller (2008) found a rough oxide layer on the SMA wire demonstrated the best interfacial strength guaranteeing a good bond between the wire and the epoxy matrix. These results will need to be investigated further to ascertain the true relationship with woven structures.

3.2.7 Summary of NiTi components

After reviewing the available literature the wire for the initial sample investigations into the general properties and weavability of NiTi was supplied by Tony Anson. This wire was of 100µm and

150µm with a black oxide finish and trained to a 20mm diameter spiral (Table 21). From the results of these initial samples, which will be further discussed in section 4.1.1.3, the decision was made to work on the lower end of the range discussed in section 3.2.6.1 with wires of around 150µm and lower. These wires are about half the diameter of those used by Chan but the upper end of the selection is comparable to those used by (Parlinska, Balta et al. 2000; Parlinska, Clech et al. 2000; Stalmans, Tsoi et al. 2000; Boussu, Bailleul et al. 2002) in the development of composite structures. The reason for this decision is twofold, firstly the use of a higher number of finer wires is more conducive to the development of controlled and even patterns of movement because of the increased number of instances with which the supporting structure will contact the wire. Secondly because of their smaller diameter, the wires will have a less detrimental visual and tactile impact on the supporting textile, negating the need for the spinning of composite yarns and consequently the reduction of accurate insertion.

Size of wire	Type	Condition	Finish	Supplier	Lot no.
100µmØ	Superelastic (NT) (Af 28°C)	Trained 20mm Ø coil	Oxide	Thomas Bolton Ltd	3003-2-3
115µmØ	Superelastic (N) (Af -15°C)	Fully annealed	Pickled	Memory Metalle	0182
150µmØ	Superelastic (Af 28°C)	Trained 20mm Ø coil	Black Oxide	From stock (Tony Anson)	Unknown
152µmØ	Actuator (B) (Af 35°C)	Fully annealed	Oxide	Memory Metalle	0705
25µm x 445µm	Actuator (H) (Af 95°C)	Fully annealed	Oxide	Memory Metalle	1114
50µm x 420µm	Superelastic (N) (Af -15 °C)	Fully annealed	Oxide	Memory Metalle	1115
170 µm x 900µm	Actuator (B) (Af 35°C)	As drawn	Oxide	Memory Metalle	1130

Table 21 Properties of selected NiTi components used.

As mentioned in the introduction to this section the choice of NiTi was finally determined by the availability of wires held in stock. After contacting a number of suppliers the decision was made to use Memory Metalle GmbH as the supplier of NiTi for this investigation. The reason for this decision was the broad range of wire finishes and diameters held in stock and more specifically the availability of a selection of ribbons which were key to the proposed evaluation (Table 21).

The round wire selected for this investigation and used throughout phases 2 and 3 was of 115µm and 152µmØ. Although the 115µmØ wire was slightly larger than the planned 100µm wire supplied by Anson, it was chosen because of its pickled surface finish which would be compared against the black oxide finish of the 100µm and 150µm wires and the oxide finish of the 152µm wire which was also selected from Memory Metalle GmbH.

Although restricted, the choice of ribbons used provided dimensions which would allow comparison on a number of different levels. To aid continuity and comparison of results all the ribbons have an oxide finish. Three sizes of ribbon were chosen, 25µm x 445µm, 50µm x 420µm and 170µm x 900µm. The choice of the smaller two wires would allow a good evaluation of the thickness of the ribbon used as the 50µm x 420µm is twice the thickness while being only 25µm wider and as a result both ribbons had the same external dimensions (940µm) (Table 22) which would allow for an evaluation of the relationship between surface area and proportions of the ribbon. For the largest of the ribbons the aim had been to use a wire with an external surface dimension of 1889µm and width of between 840µm and 890µm which would have served as a good comparison to the other two ribbons' external surface dimension and been approximately twice the width. However, this was not possible and the final choice from available stock was 170µm x 900µm. Although not a direct comparison the width was only slightly greater and would still allow for some direct comparisons to be made.

Cross sectional dimension	Circumference / external surface measurement (µm)
100µmØ	314µm
115µmØ	361µm
150µmØ	471µm
152µmØ	478µm
25µm x 445µm	940µm
50µm x 420µm	940µm
170µm x 900µm	2140µm

Table 22 Showing the cross sectional dimensions and related cross sectional surface area of wires used.

Keeping the number of different surface finishes for the selected wires low allowed better comparisons to be made between the other variables of the wire, yarn and supporting structure. As a result of the difficulty in acquiring NiTi samples which had different surface finishes whilst maintaining continuity with regards to dimensions, it was decided that lengths of the selected wires would undergo an additional heat treatment to apply an additional oxide layer to that of the purchased state. This heat treatment was undertaken in a convection oven at 260ºC for six hours. The results of this process can be seen in the results from the SEM images and EDA charts in section 3.2.7.1. In addition to the testing of composite fabrics with integrated NiTi wires, supplementary samples were woven with an additional weft yarn of the supporting fabric. These additional samples would be used as a control from which the integration of the NiTi could be assessed. This process would have been impractical with the Duron samples because after the heat treatment the additional integrated fibre would have been indistinguishable, so in place of the inserted NiTi weft pick, an additional mercerised cotton weft yarn was used.

3.2.7.1 Characterising surface features of SMA

Characterisation of the surface finish of the NiTi components used in phases 2 and 3 was undertaken using a scanning electron microscopy (SEM) system (JEOL), producing both images and energy dispersive X-ray (EDX) analysis of the sample surfaces (Figure 35). Producing images up to 500,000 times magnification, SEM techniques have the advantage over light microscopy, because the images derived do not suffer from a decreasing depth of visual field as the magnification increases. The method used to generate images is based upon electrons impinging upon the surface of the material being imaged. When electrons are emitted and directed at a surface, they displace electron shells of the sample material; the energy lost or gained by this impingement process is then detected and the data correlated to produce an image. Back scattered electrons, resulting from impingement, produce x-ray emissions that can be detected, yielding compositional information about surfaces and sub-surfaces to a depth of a few nanometers.

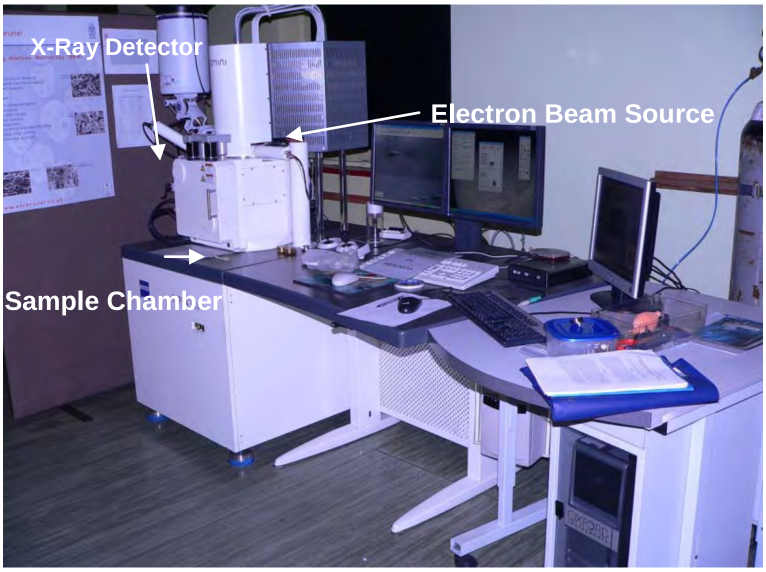


Figure 35 Zeiss Supra 35VP Scanning Electron Microscopy System fitted with an Energy Dispersive X-ray (EDX) composition analysis system (original in colour).

Preparation of the samples was required for the production of good images and critical for the EDX analysis. The NiTi wire samples were first degreased and cleaned using a sequence of a wash in trichloroethylene in a safety cabinet, followed by a wash in acetone and then a final rinse in double distilled deionised water. This cleaning process was performed so that the samples presented to SEM were free from any extraneous residues on their surface. Thorough cleaning, in the same way as for the NiTi wires, was not possible for the yarns, so they were taken from deep within the cone just prior to the final preparation of the samples to reduce the risk of contamination and acquisition of unwanted particles (for SEM images of the yarn see Figure 28, Figure 30, Figure 31 and Figure 32). To achieve a clearer SEM image of the fibres, the yarns were mounted in a relaxed and separated state and as such were not used for measuring the diameter of the yarn.

Images created through the use of SEM analysis were for comparative topography and morphology investigations to inform the results of the extraction testing. SEM images were produced to provide an understanding of the surface properties of the NiTi wire being extracted (Table 23). Images (c - f) show the pitted surface of the 115µm NiTi wire that had been pickled after the final drawing down of the wire. This is in marked contrast to the smoother oxide finishes of the other samples, which show a comparatively smooth if uneven surface with fine longitudinal striations formed during the drawing down process. As a result of the differences in the wires as bought surfaces, direct comparisons cannot be made between the 115µm NiTi wire and the other samples but have been included as a point of reference. When visually comparing the surfaces of the other NiTi components, there is no discernible difference between the images of the NiTi in the as purchased condition when compared to the samples which underwent the additional heat treatment.

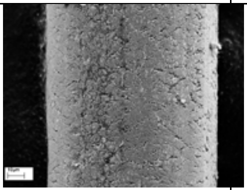
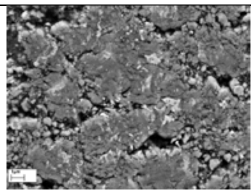
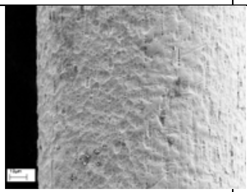
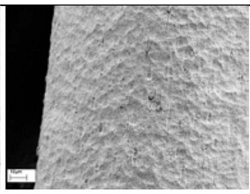
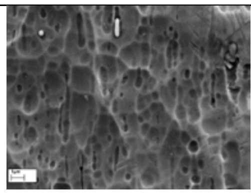
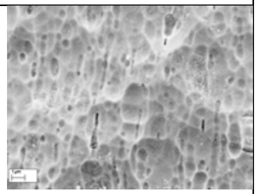
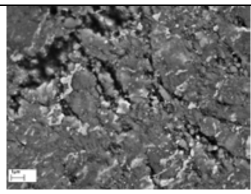
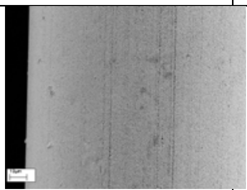
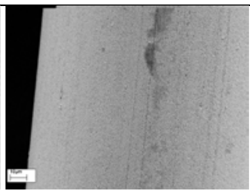
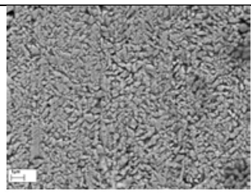
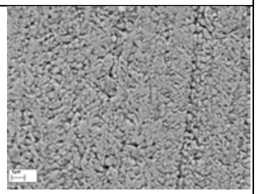
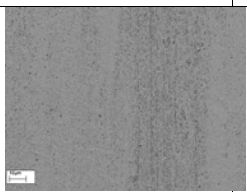
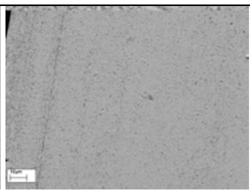
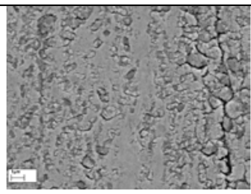
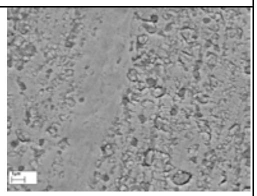
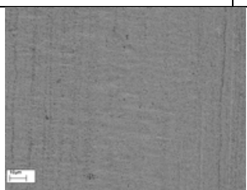
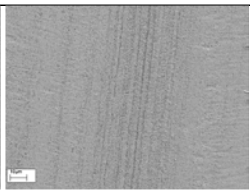
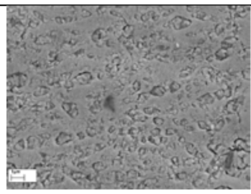
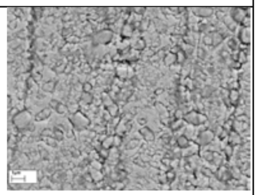
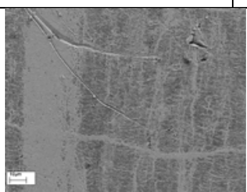
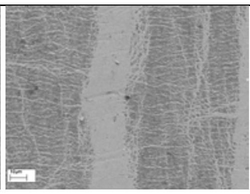
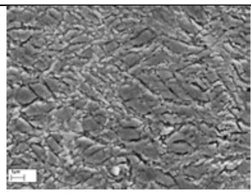
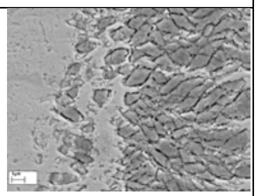
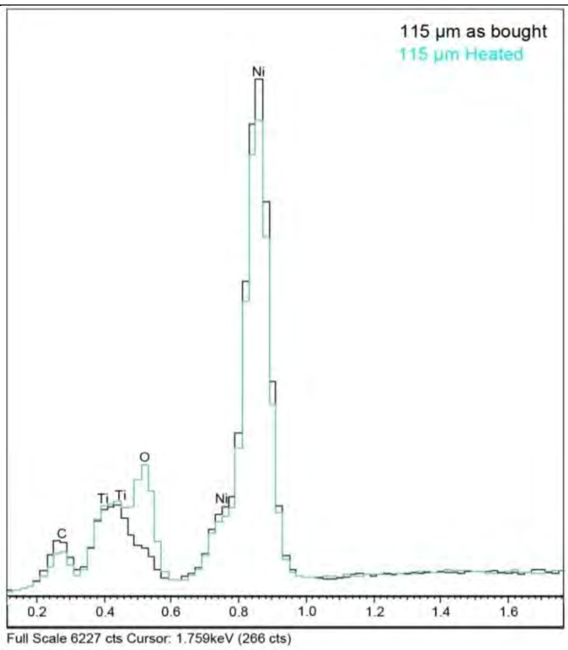
	2.6k x magnification		20k x magnification	
	Surface as purchased	Surface after additional heating	Surface as purchased	Surface after additional heating
100µm wire Black oxide finish	 a.		 b.	
115µm wire Pickled finish	 c.	 d.	 e.	 f.
150µm wire Black oxide finish			 g.	
152µmwire Oxide finish	 h.	 i.	 j.	 k.
25µm x 445µm ribbon Oxide finish	 l.	 m.	 n.	 o.
50µm x 420µm ribbon Oxide finish	 p.	 q.	 r.	 s.
170µm x 900µm ribbon Oxide finish	 t.	 u.	 v.	 w.

Table 23 SEM images of NiTi components used in this investigation.

At the same time, investigations into the surface composition of the NiTi were conducted using energy dispersive X-ray (EDX) analysis (Figure 36 and Figure 37). The EDX analysis was required to evaluate the presence and levels of increased Ni or Ti oxides on the surface of the wires resulting from the additional heat treatment. Although the differences in surface finish were not conclusive from the SEM images, the EDX results do indicate that on the 115µm and 152µm wire samples tested a clear increase in oxides can be seen on the surface of the wires which underwent the additional heat treatment. To fully understand and quantify the surface morphology and topology, further investigations would be required that investigate broader and more noticeable differences in surface topology; for example pickled, polished and different oxide levels.



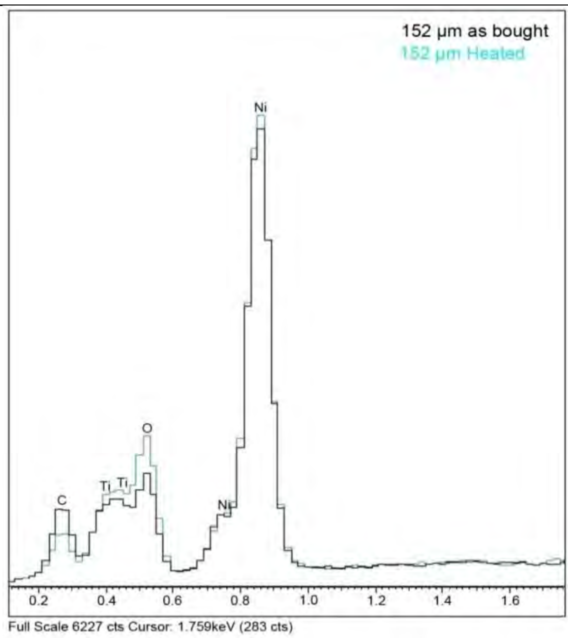


Figure 36 EDX analysis of 115µmØ NiTi wire.

Figure 37 EDX analysis of 152µmØ NiTi wire.

3.2.8 Production of samples

A strict protocol was used for the production of samples and the selection of variables to be considered. This established boundaries within which the variables could be tested and evaluated maximising continuity and as such the comparability of the results. Focusing on the setup of the loom, the method of construction and dimensions of the samples and the placing of the integrated NiTi component were derived.

3.2.8.1 Loom

Although limiting with regard to informing larger scale automated production, the decision to work on small hand woven samples has meant that a wide range of parameter changes has been possible, which would have been both very expensive and time consuming to achieve on an automated loom. Based on this decision a twin beam eight shaft Harris hand loom was initially used for the production of samples in phase 2, study i. The Harris loom proved adequate for the production of these initial samples but the limited number of shafts would restrict future developments. To provide future continuity in production of samples the decision was made to switch to a loom with a greater number of shafts and control. All the subsequent samples in phase 2, as well as those in phase 3, were woven on a 24 shaft Arm AG CH-3507 electronic dobby hand loom, with a sliding beater. This loom still allowed for quick adjustments to the weaving parameters and design whilst improving quality of the sample and the accuracy of the insertion of the NiTi wires with the use of the sliding beater. Subsequently within this investigation, the evaluation of weavability is limited to the production of small hand woven samples. Whilst this is adequate for the testing and evaluation of the interfacial relationships between NiTi components and woven structures, future research would need to investigate and address the production methods on automated looms. Comparative studies by Boussue (2002) into the weavability of comparable NiTi and stainless steel wires (which are currently commercially woven), demonstrated a reduction in weaving defects from the NiTi samples. It is considered a fair assumption that, with current automated weaving technology, future developments and automated production would not be restricted due to weaving faults.

3.2.8.2 Sample dimensions and construction

Unlike the other variables explored in this investigation the size of the sample and how it is handled while testing are not constituent elements. In spite of this the influence they can have on the interfacial relationship of the structure, supporting yarn and integrated component can have dramatic effects on the material’s performance. The investigation of sample size and working conditions will give an indication of how the relationship between structure and integrated component can be influenced by these additional factors. The size and working parameters of the material will often be governed by the application itself but, through an understanding of the influence these factors have, adjustments can be accounted for and predicted.

In consideration of the cost and limited availability of the NiTi wire all the samples were woven to a width of 100mm (perpendicular to the warp). To aid the comparison of samples during testing, three related sample sizes were chosen which worked on a progression of characteristics. The exceptions to these basic dimensions were samples 17 – 23 which were woven to a 50mm width so that they could be produced from the existing warp. This decision did not affect the assessment of the samples as the evaluation was based on weavability and visual defects rather than objective evaluation.

The initial sample size was 50mm x 30mm (used extensively in all the testing in phases 2 and 3). They were produced as 100mm x 30mm samples (Figure 39 (b)) that were later cut in half (Figure 38 (a) and Figure 39). The cutting of these samples in two, effectively allowed the dual testing of the same sample using both the basic mass loading technique and the computer controlled tensile / compression testing machine. The second sample size was again 100mm x 30mm but these samples were tested at their full size (Figure 38 b). The results from the 100mm x 30mm could be directly compared with the results from the 50mm x 30mm samples indicating the effect of increased sample length. In addition, the 100mm x 30mm samples could be compared directly with the final samples which also had a length of 100mm (100m x 100mm). In contrast to the previous samples which were only exposed to the tension resulting from extraction force, the 100mm x 100mm samples were tested whilst under tension perpendicular to the line of extraction (Figure 38 c). This allowed an evaluation to be made of the effect the tightening of the fabric's crimp had on the wire and subsequently on the extraction loads. Each sample had an additional 10mm of waste added to its length to maintain the integrity of the actual sample before testing.

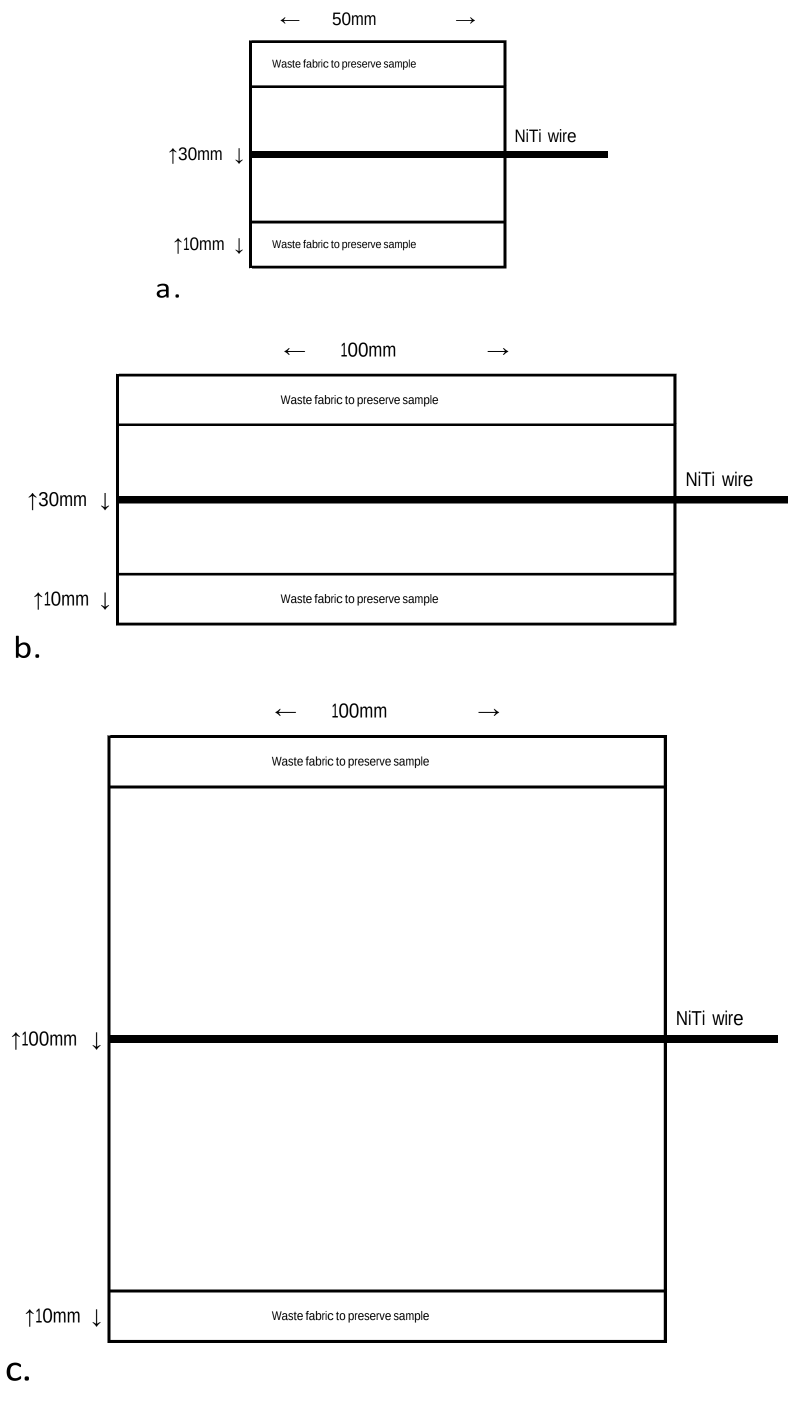


Figure 38 Schematics of the three sizes of sample woven throughout the investigation.

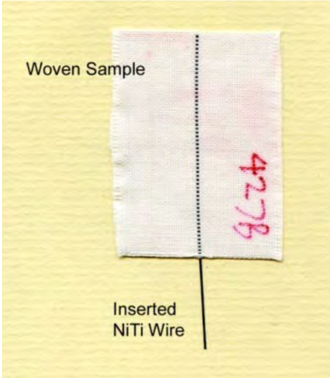


Figure 39 Example of a woven sample with inserted NiTi wire prior to extraction (original in colour).

3.2.8.3 Heat treatment of Duron samples

After being removed from the loom, the Duron samples underwent a heat treatment process. This was conducted using an A. Adkins Mk 6 heat transfer press. 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 Duron yarn which has a melting point of ~160°C, bonding it to the NiTi wire and supporting cotton yarn (Figure 40). After heat setting the samples were trimmed to 30mm x 100mm for bend testing then to 30mm x 50mm prior to the extraction of the NiTi wire.

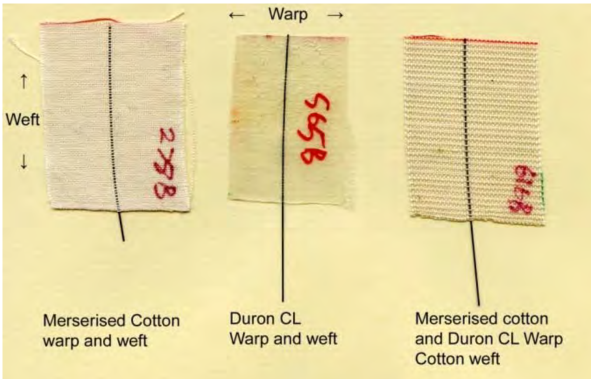


Figure 40 Examples of woven samples after heat treatment (original in colour).

3.2.9 Test methods

Owing to the novel and previously unexplored area this investigation covers, a new method of evaluation and test parameters were needed. This new methodology would need to be able to explore the dynamic relationship between an inserted NiTi wire and woven structures for the production of controlled patterns of movement as well as its appropriateness for use as an apparel fabric. As will be discussed in the following section a variety of methods were used which were adopted or adapted from other test methods for this specific evaluation. To test and develop a core knowledge of the possibilities that could be created in this dynamic relationship the key variables identified were systematically tested and evaluated using both subjective and objective methods.

Subjective evaluations of visual and tactile properties were carried out in conjunction with comparative topography and morphology investigations using a scanning electron microscopy system. Investigations regarding composition of the shape memory alloy surface were conducted at the same time using energy dispersive X-ray analysis. The subjective evaluations were conducted to assess:

- Weavability and ease of inserting the NiTi into the woven structure
- Integrity of woven structure after weaving
- Handle
- Aesthetic appearance

Objective evaluations were conducted using bend testing, basic mechanical mass loading to extraction and computer controlled tensile / compression testing to extraction. These evaluations were conducted to assess:

- How the insertion of different NiTi wires affects the stiffness of a textile.
- How the woven structure promotes or impedes the movement of an inserted NiTi wire.
- How the surface of an inserted NiTi wire can promote or impede friction with a supporting structure.

The aim of this investigation was to gain a rigorous and focused grounding which could be used to inform later development. Ultimately evaluations would be required that explored samples under specific conditions relating to the final application. After an initial review of current testing methods the specific test procedures used in this investigation are discussed.

3.2.9.1 Subjective evaluation

The main focus of this work is on the investigation of the mechanical properties of and the relationship between inserted NiTi wires using a variety of structures and supporting yarns. Although this relationship will be fundamental to the success or failure of controllable textiles, the study has not neglected all consideration for tactile qualities.

The suitability of materials used particularly for apparel fabrics is a complex interrelationship of fibre, yarn and structure. Due to the intimate relationship between wearer and material, the less tangible qualities of handle, aesthetics and emotional response are as important as tangible qualities such as tensile strength, flexibility and durability (Fangueiro, Franzo et al. 2006).

"… comfort is not only a function of the physical properties of materials and clothing variables, but must be interpreted within the complete context of human physiological and psychological response. Human expectations, or stored modifiers, that filter or influence our judgment about comfort based on a personal experience must also be considered" (Barker 2002).

From birth we develop an intimate and personal relationship with textiles that is influenced by our experiences, from our environment, culture, social position and fashion, to our age, health and emotions. It is because of this diversity of experience that the ability to universally define the properties of a textile for apparel is so difficult. In an effort to standardise the subjective test method Mackay produced instructions to inform the tester how the fabric should be handled during assessment (Figure 41).

[redacted]

Figure 41 Methods and procedure for the subjective evaluation of a fabric's handle, produced by Mackay (Bishop 1996).

In recent years fresh attempts have been made to use technology to simulate the handle and texture of a textile in a virtual environment (Meinander 2008). This involves the reading of fabrics through sensors that convert impressions of stiffness and texture into a digital format that can be replayed through an actuated glove giving an impression of the original fabric. Although this method of transmitting tactile properties digitally is at an early stage of development basic sensations of weight, stiffness and texture have been delivered.

3.2.9.2 Fabric Objective Measurement (FOM)

The subjective evaluation of textiles has remained the main method of analysing and conveying the properties of textiles for apparel even to the present day. This had been carried out by personnel with traditional textile knowledge and many years of experience (Hu 2004). As a result of the lack of newly trained personnel coupled with increasing levels of automation and digital communication being used in other areas of the supply chain, the need to develop a method of objectively quantifying the properties of textiles is becoming critical to maintaining a competitive edge. The need for objective data on textile performance has been highlighted with the increasing use of technical textiles in architectural, engineering, aerospace and medical applications where specific properties, characteristics and limitations need to be quantified.

The two most prominent and widely used textile testing systems are: FAST (Fabric Assurance by Simple Testing), developed to provide the industry with a simple, robust and relatively inexpensive means of measuring the properties that affect the tailoring performance and appearance of a fabric; and KES-f (Kawabata Evaluation System for Fabrics), developed as a systematic method of quantifying the mechanical properties of a textile. Prior to the development of these systems various methodologies were in use that utilised methods and equipment developed for the testing of non textile materials. These systems introduced a number of textile focused tests like dimensional stability, rigidity, bending and surface qualities (Hu 2004) which served to provide a better understanding of the specific properties of a textile.

Due to the adaptive nature of textiles objective measurements are also open to difficulties in accuracy and extreme care is required during testing and quantifying the physical properties to maximise the repeatability of the results. The accurate testing of textiles can be affected by the smallest differences while handling and cutting samples prior to testing or when placing the sample in the testing equipment. Although these systems are widely seen as an accurate and reproducible method of objective measurement (Hu 2004; Stylios 2005), in two inter-laboratory tests by Mahar, Dhingra et al. and Ly (1987; 1989) reported by Bishop (1996), it was concluded that results within the same laboratory and with the same operator showed good repeatability, but the results between laboratories showed notable differences.

3.2.9.2.1 Bend testing

A flexometer was used to test the bend angle and bending rigidity of a fabric (Figure 42). Two test methods have been employed by the industry, the first uses a sample of a fixed length and measures the bend angle while the second method uses a fixed angle and measures the bend length. Bend testing is used to assess the rigidity of samples and, in comparative studies, to evaluate the effect a seam or trim has on the overall dynamics of the fabric. For this reason it was considered a valuable assessment tool to understand the relationship between the different woven structures, yarn types and how the different NiTi wires affect the rigidity of the sample.

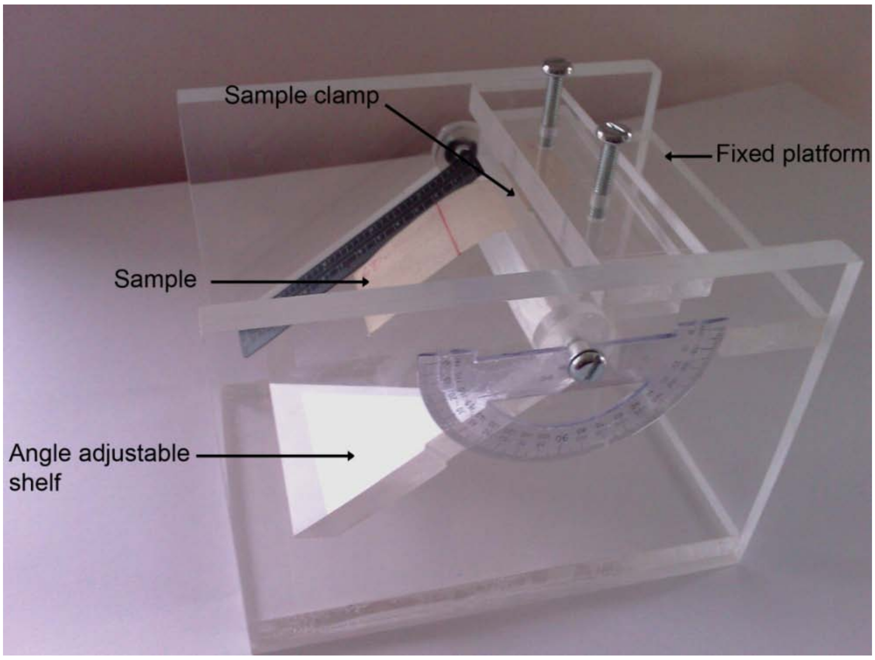


Figure 42 Flexometer with test sample (original in colour).

The first method measures the bending angle of a fabric cantilever with a constant length (Figure 43). A sample is placed and held in position on the horizontal platform with a fixed length extending beyond the pivot point and onto an angle adjustable shelf. Once set, the adjustable shelf is slowly lowered until the point is reached at which the sample loses contact with the shelf. At this point the angle of the shelf is recorded, providing the bend angle.

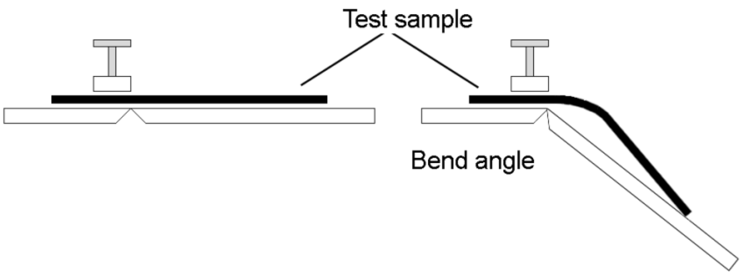


Figure 43 Schematic of bend angle testing.

The second method, which is used as part of the FAST testing system, uses the same horizontal platform but the angle of the adjustable shelf is fixed at 41.5° from the horizontal. This angle aids subsequent calculations within the FAST system (Figure 44). The sample being tested is then placed on the horizontal shelf and slowly advanced so that one end extends over the pivot point. This is continued until the sample bends and makes contact with the angled surface. At the point of contact a measurement is taken of the length of fabric extending past the pivot point which is used as the bend length.

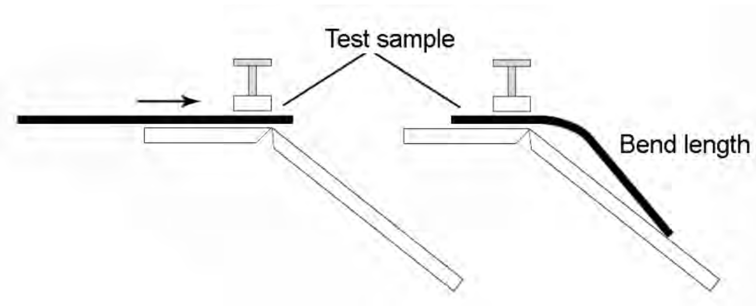


Figure 44 Schematic of bend length testing.

As part of the testing of the samples in phases 2 and 3 results were recorded using both methods. It was found, however, that as a result of the direct interaction and movement of the sample during testing, the bend length test method showed inconsistencies and after an initial comparative evaluation between the methods these results were discarded.

3.2.9.2.2 Extraction testing

Surface friction testing is part of both the KES-f and FAST systems but these methods only convey the friction between surface properties. Although the results for surface friction would be influenced by the woven structure, it would not take into account the influence the interlacement and tightness of the cloth has on the integrated NiTi components. To quantity the influence of these additional variables extraction testing was used, with the load on the integrated NiTi component being recorded at the point it was released from the supporting woven structure. A comparable pull-out test was employed by Balta, Michaud et al. (2000) to determine the average interfacial shear stresses of NiTi wires embedded at different depths in resin cylinders prior to the development of composite beams. Also as part of these tests the surface condition of the wire was evaluated. When the extraction load is high it indicated that the integrated element is held firmly within the structure, maximising possible shape transfer and promoting a stable structure from which secondary movement can be controlled.

Data was gathered and two experimental setups were devised to investigate the relationship and mechanical interaction between differences in the composite structures and inserted NiTi wires. The test methods used were mechanical mass loading to extraction, which was used to evaluate the static loading of the composite samples and computer controlled tensile testing to extraction which recorded the dynamic friction in the composites. The analysis of the data obtained was used to quantify the extent to which the woven structure could be used to facilitate or impede the direct transfer of control from the wire to the supporting structure. These results also demonstrate the level of secondary control available from a given composite and how this can be adjusted across the textile to provide the required control across the structure maximising the anisotropic nature of the textile.

Mechanical mass loading (static friction)

The device used to perform the mechanical mass loading to extraction tests, was designed to promote ease of use and to allow the swift turnaround of sample testing while maintaining the accuracy and repeatability of results. The device consisted of a simple ‘T’ structure with free running pulleys between which a fine cord ran from a gripper to hold the exposed wire and a container which would receive the mass load, which was water (Figure 45). The decision to use water instead of solid (incremental) weights as the mass, increased the resolution of the results. The reason for this is that water could be added slowly, whereas solid weights would need to be applied at predetermined increments, for example 10g. Some discrepancy may be present using the water method, due to the tester’s reaction time when stopping the flow of water. This was minimised across the samples as the same operator performed all the sample testing and the speed at which the water was added was kept slow and constant reducing the impact of reaction time.

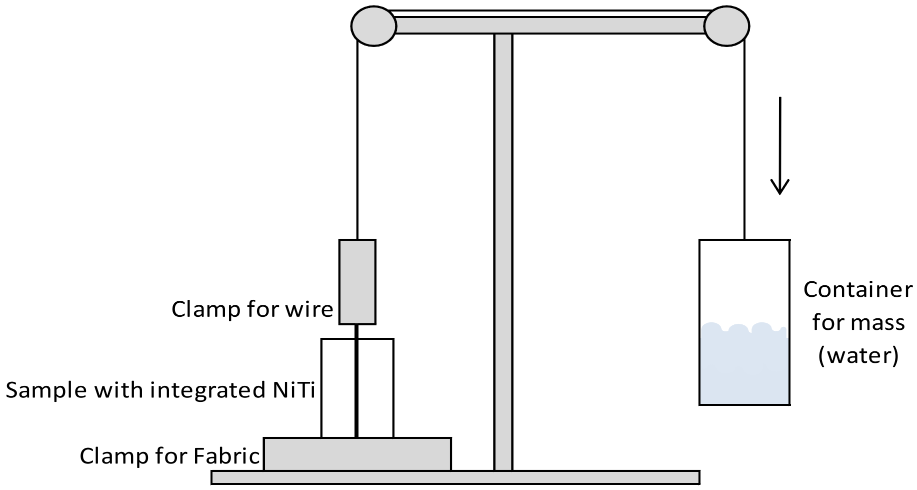


Figure 45 Test set-up for the extraction of NiTi components using mass loading.

The positioning and setting of the sample in the clamps was critical to maximise the reliability of the results. Any change in the handling, angle or proportion of the sample held in the grippers would change the dynamics of the sample and affect the results. An additional consideration was the clamping of the fabric end which had the integrated wire. To accommodate the un-restricted removal of the NiTi wire from the sample a special set of grippers with a 1cm groove cut into each side was created. This groove accommodated the wire ensuring that the force required for extraction was purely the result of the effects of the supporting fabric on the wire and not that the wire was being held by the grippers. The integrated wire was placed centrally to an etched line (Figure 46 a) to ensure even extraction and to maintain continuity between samples. To ensure each sample was held in the grippers to the same depth the samples were placed so that they made contact with the base of the grippers which were 1cm high, ensuring that only 1cm at the base of each sample was held, leaving the rest free (Figure 46).

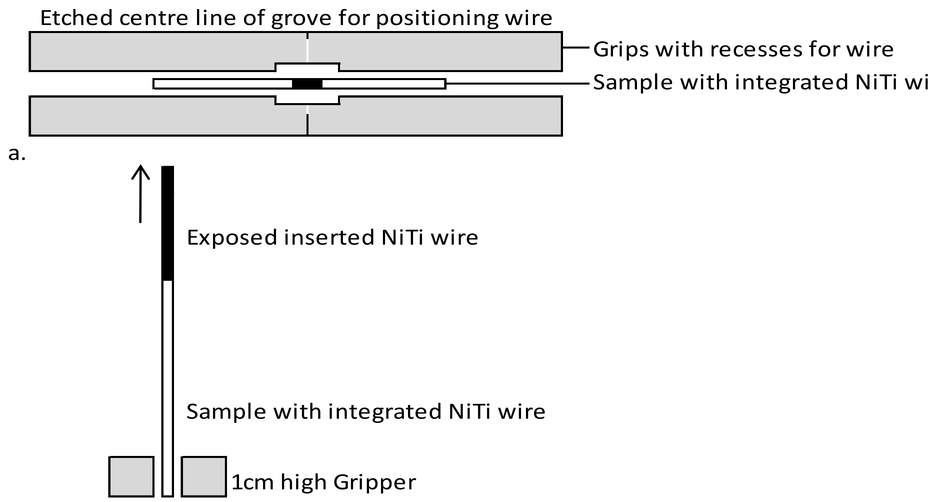


Figure 46 Schematic of grippers holding the test sample. a. Grippers and sample viewed from above. b. Grippers and sample viewed from the side.

The test method above was used on all the 30mm x 50mm and 30mm x 100mm samples. An additional range of samples were also tested using an adapted version of the above test method. This method was designed to compare the difference in force required to extract the wire from a textile with no lateral tension, as can be seen in the first test method, and a sample under lateral tension. Placing a sample under lateral tension during extraction testing will tighten the crimp of the yarn around the NiTi component holding it more securely within the structure.

For this second test method, samples of 100mm x 100mm were used so a comparison could be made with the 30mm x 100mm samples. To facilitate the inclusion of a lateral tension on the sample the test device was altered to the configuration shown in Figure 47. The sample was rotated 90º and was clamped (neither set of clamps had the groove used in the first test method) parallel to the NiTi wire. Instead of a variable weight being added at this point a fixed weight of 5kg was used, putting each sample under 5kg of lateral tension during testing. Although the loading of individual threads across the NiTi would vary depending on the epi for each sample, this method of applying lateral tension would ensure an even and comparative overall loading across the inserted length (100mm) of the integrated NiTi. This setup held the sample in place while an additional pulley was added. This pulley was at the same height as the integrated NiTi wire to minimize distortion of the sample and maintain continuity with the inline extraction performed in the previous test method. The exposed NiTi wire was attached via a gripper and cord over the additional free running pulley to a container into which the variable weight was to be added to acquire the extraction force.

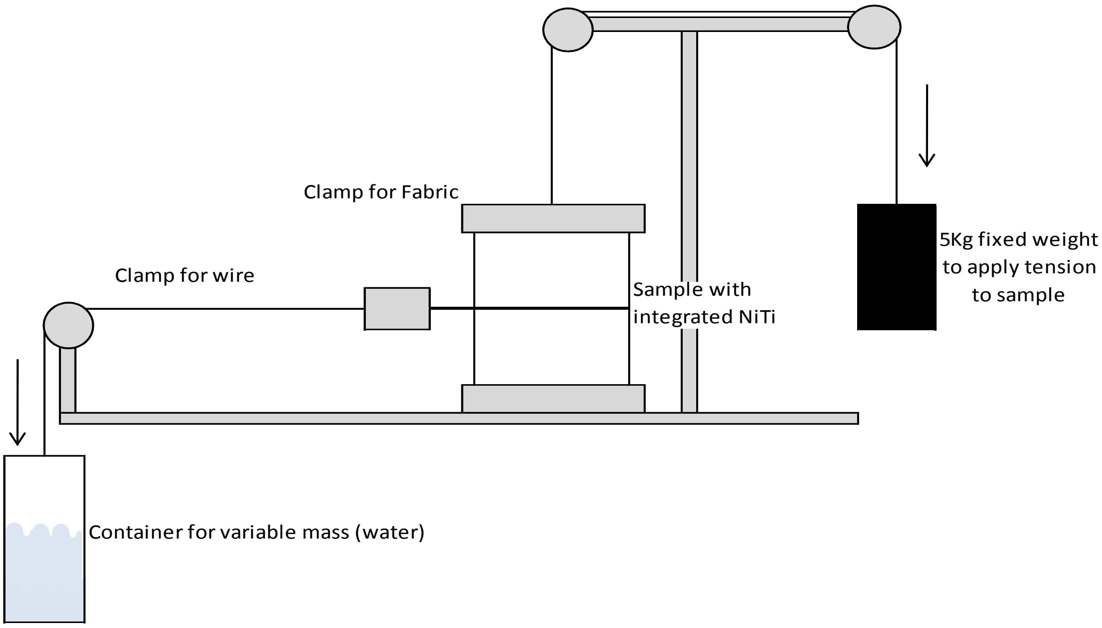


Figure 47 Schematic of the setup used for the extraction of the NiTi component while the sample is under tension

For both the test setups described above, upon the final extraction of the wire from the sample, the container with the added water was weighed on a set of balances with an accuracy of 0.1g. The weight recorded took into consideration the container weight and also the weight of the gripper holding the wire which although small, acted as a counter weight in the first test method. Combinations of these two methods (appropriate to sample dimensions) were carried out on all the samples, in phase 3 and also some of the samples with selvedges in phase 2, study iii.

Computer controlled tensile / compression tester (dynamic friction)

To obtain results relating to the dynamic friction of NiTi wires integrated into different woven structures a computer controlled tensile tester was used. The test setup used an Instron model 1011 tensile and compression test machine connected to a Schlumberger SI 3535D data logger (Figure 48) with the readings being exported to a PC Computer and into a Microsoft Excel spreadsheet for analysis.

Figure 48 Instron computerised tensile test machine used for dynamic friction tests (original in colour).

As with all the testing, the handling and positioning of the samples in the clamps was critical to maximizing the reliability of the results. To maintain continuity this test setup mimicked, where possible and practical, the test set-up used for the basic mechanical mass loading. This can be seen predominantly in the positioning of the samples in the grippers and although different grippers were needed to interface with the Instron test machine the same protocols were applied. The fabric ends of the samples were held at a depth of 1cm in the grippers with the integrated wire positioned centrally within the 1cm groove to prevent gripping of the wire itself (Figure 49). The free end of the wire which protruded from the woven sample was held in a conventional clamp.

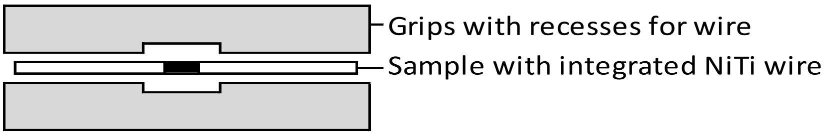


Figure 49 Schematic of sample held in the grippers used with the Instron test machine.

All the samples were tested using a 500N load ring and the extraction speed was set at 100mm per minute with 10 readings recorded every second (Figure 50). This combination of extraction data acquisition provided a total of 300 readings for each sample and showed the build up to peak force and the subsequent drop off once the wire was released from the structure.

a.

b.

Figure 50 Woven sample held in the Instron tensile test machine. (a) Sample positioned ready for testing. (b) Sample part-way through testing and extraction of NiTi wire (original in colour).

In addition to the tensile testing to extraction discussed above, conventional tensile tests were performed on the yarns used to form the supporting structure (discussed further in section 3.2.4.6). The results from these tests are used to understand the proportional relationship between the force needed to extract the wire and the inherent strength of the supporting fibres.

3.2.10 Recording the results

The planning and handling of the data from the samples tested was critical because although the investigation had very focused aims the limited research in the area provided little in the way of a framework or foundation from which to expand. The clear and concise development of this foundation was important in framing the investigation as a whole. Although the selection of key variables had been conducted, the identification and recording of other active elements was required and integrated into a precise, consistent and readable format.

The work of Tufte (1990; 2006) became an important guide and influenced the design and mapping of the test variables and results. Tufte has studied, evaluated and written extensively on the graphic representation of complex quantitive information. The theory Tufte proposes is to reduce the “graphic junk” that computers have made it easy to employ and to keep the “graphical ink” to a minimum while maximizing the “data Ink”. “Data graphics should draw the viewer’s attention to the sense and substance of the data, not to something else” (Tufte 2006).

After the identification of the variables to be tested at each phase, a simple tick box chart was constructed (appendix B.) with the individual sample numbers running along the top and the variables down the side. The variables were grouped together in related categories to aid the reading of the parameters relating to individual components. A consistently repeated pattern was adopted for the development of sample. These simple charts were used predominantly for the development and charting of sample production but being very visual and less text based can be used as a reference for samples, properties and the identification of any chosen variable. At the bottom of each sample's column the results of the bend and extraction tests are included as a quick reference.

From the tick box chart described above, text based versions (Table 9 and Table 24) breaks the samples down into the individual phases and studies identifying only the key information relating to that particular study. After the development of the initial samples (1 – 29) which were more exploratory in their design, the samples were grouped together based on the similarities of repeated difference. An example of this is in defining the integrated element which consistently follows the same pattern; Supporting Yarn, followed by the NiTi elements in the following order 115µm, 152µm, 25µm x 445µm, 50µm x 420µm and 170µm x 900µm.

The final method of recording the data was the creation of a Filemaker Pro database. The information in the database can be accessed in two distinct forms. The first is in a printed format that consists of a main table with the individual samples attached. Kept in lever arch files this single page per sample record provides an in-depth record of all the variables relating to each sample including materials used, construction testing performed and results as well as general and detailed images and specific comments. As well as the printed version (kept with author) the database in electronic format (Filemaker pro format) is provided as a fully searchable and sortable resource in (appendix C.). Searches can be made using any of the variables or construction values as well as the results making it a versatile and valuable resource for future investigations. Due to the limited nature of access to the Filemaker pro format a second electronic version is provided (appendix D) as a PDF file which is accessible via Adobe reader. Whilst it contains all the information in the main sample view, this electronic PDF version cannot be sorted.

3.2.10.1 Box plots

Box plots were chosen as the main graphical format for showing the data as they are able to display differences and trends between sets of results with similar patterns of variables without making assumptions about the underlying distribution of data. They consist of three main parts (Figure 51):

- The top and bottom of the box relate to the 75th and 25th percentile respectively, with the 50th percentile or median represented by the central line.
- The whiskers denote the extent of the remaining results although extreme results are plotted separately as outliers.
- The outliers are results that fall in the 1st – 50th and 75th – 100th percentile of the results but at a distance of more than 1.5 x the box length (O) and more than 3 x the box length (*). To provide a clear understanding of the data they are identified separately as they can indicate measurement errors or extreme results that may require further investigation.

When analysing the data in the charts, a smaller distribution of results and subsequently smaller box and whiskers, would indicate that the selection of variables being studied plays a dominant role in the behaviour of the NiTi components in the woven structure; conversely, a larger distribution of results would indicate that there are additional variables exerting a strong influence.

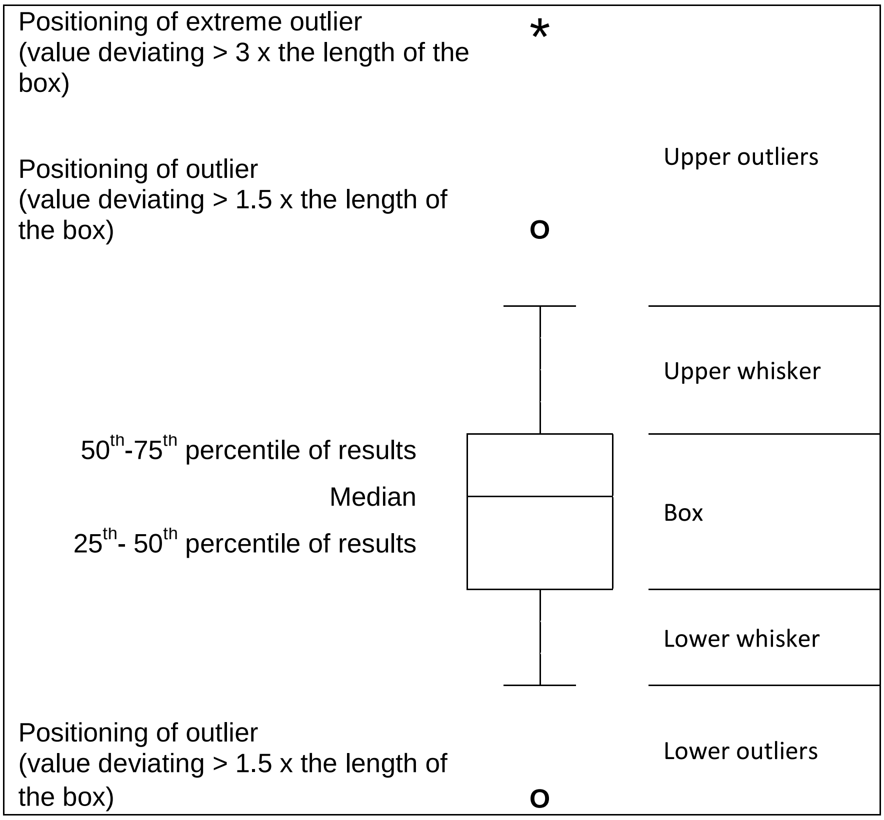


Figure 51 Structure of the box plots used for the results.

3.2.11 Conclusion

This chapter has identified key variables relating to the woven structure, yarn type and set of samples to be woven for the following phases (Table 24) as well as those for the NiTi component including dimensions, section and surface finish. Based on existing methods of assessing material and textiles a range of test methods was identified and discussed. These included bend testing to evaluate the rigidity of the samples, and both basic mass and computer controlled tensile testing to extraction. The tensile tests would facilitate an understanding of the static and dynamic interfacial relationships between the inserted NiTi components and a variety of supporting textile structures.

Variables	Individual elements investigated	Phase 1	Phase 2			Phase 3			Aims of differences in variables
			Si	Sii	Siii	Si	Sii	Siii	
Materials									
Supporting yarn and yarn combinations	Mercerised cotton	Theoretical evaluation and selection of variables	x	x	x	x	x	x	Investigating the effect that the composition of the supporting structure has on the relationship with integrated NiTi components. Combinations of Duron yarn were used to evaluate and compare the effect a heat set polymer matrix has both as a single component and combined with mercerised cotton yarn.
	Viscose		x						
	Kevlar						x	x	
	Polyester		x				x	x	
	Duron (pp)						x	x	
	Mercerised cotton warp Duron (pp) weft					x			
	Duron (pp) warp mercerised cotton weft						x	x	
	Duron (pp) and mercerised cotton warp, mercerised cotton weft						x	x	
Woven structure	Plain weave		x	x	x	x	x	x	Investigating the effect different supporting structures have on the integrated NiTi component.
	Plain weave and 2/2 twill		x	x	x	x	x	x	
	2/2 twill		x	x	x	x	x	x	
	6 end satin					x			
	Double cloth				x				
Sett (Using Brierley's theory of empirical maximum weavability)	Even						x	x	For the samples throughout phase 2 and phase 3, study i changes in the epi were used to evaluate the integrated NiTi's relationship to over and under sett structures. Although differing between samples, the epi and subsequent sett of the samples in phase 3, studies ii and iii was even to maximise comparable continuity between the differences in supporting yarn and structure.
	72epi (2/40cc)		x		x	x			
	84epi (2/60cc)		x						
	96epi (2/40cc)					x			
	120epi (2/40cc)		x						
	144epi (2/40cc)		x	x	x	x			
	168epi (2/40cc)		x						
Selvedges	Plain weave			x	x				In phase 2, study ii selvedges are used to balance the cloth and provide coverage for the wire ends. In study iii the selvedges are used to alter the interfacial relationship along the length of the NiTi component.
	Plain weave and 2/2 twill			x	x				
	2/2 twill			x	x				
Integrated component	Additional supporting yarn				x	x	x	x	Investigating the way in which the NiTi components' cross section and dimensions affect the relationship with the supporting structure. For each set of samples a control was also woven which consisted of an additional supporting yarn to replace the NiTi component. In the case of the Duron samples an additional mercerised cotton yarn was used.
	NiTi 100µm		x	x					
	NiTi 115µm			x	x	x	x	x	
	NiTi 150 µm		x	x					
	NiTi 152µm				x	x	x	x	
	NiTi 25x445µm			x	x	x	x	x	
	NiTi 50x420µm				x	x	x	x	
	NiTi 170x900µm			x	x	x	x	x	
Surface finish	As purchased pickled						x	x	Different surface finishes were investigated to evaluate differences between the interfacial relationship of the integrated NiTi component and supporting structure.
	As purchased oxide						x	x	
	After additional heat treatment						x	x	
Sample size	30mm x 50mm				x	x	x	x	Differences between samples of 30x50mm and 30x100mm investigated the effect of increased sample length. Differences between the 30x100mm and 100x100mm samples investigated differences between a relaxed sample and one under lateral tension.
	30mm x 100mm						x	x	
	100mm x 100mm		x	x	x		x		
Testing									
Theoretical		x							Evaluation and selection of variables.
Subjective	Visual		x	x	x				Initial evaluation of samples to inform production of future samples.
	Scanning electron microscope	x							
	Handle		x	x	x				
Objective	EDX	x							Evaluation of NiTi surface composition.
	Bend testing				x	x	x		Evaluation of correlations between sample rigidity and interfacial relationships.
	Basic mass loading to extraction				x	x	x		Investigating static friction.
	Computer controlled tensile testing to extraction							x	Investigating dynamic friction.

Table 24 Overview of samples woven in each of the phases.

4 Empirical investigation and results

Phases 2 and 3 form the empirical element of the investigation with each phase containing three studies. The investigations within these two phases evaluate different aspects relating to the integration of NiTi wires into woven structures. Phase 2 is predominantly concerned with the initial design investigation, weavability and the visual and tactile characteristics of the composite textile. With the exception of a number of samples in study iii (which underwent bend and tensile testing to extraction) phase 2 focused on subjective evaluations. The design and construction of the samples in phase 3 is based on the results of the subjective, visual and tactile evaluations conducted in phase 2. These samples make up the majority of the empirical investigation and focus on specific interfacial properties and interactions between the integrated NiTi wires and the textile structure. Evaluations using objective methods, including bend testing, and tensile testing to extraction of the inserted components, produced a large body of results and greatly informed the understanding of the interfacial relationship between inserted NiTi components and woven supporting structures.

4.1 Phase 2

Phase 2 covers the initial design development of flexible NiTi composite woven textile structures, and the creation of samples with visual and tactile qualities appropriate for apparel and medical textiles. The production and evaluation of samples in the first two studies in phase 2 are concerned solely with the design, development and understanding of the insertion characteristics of NiTi wires and ribbon, focusing on the weavability and handle of the fabric. The weavability of NiTi has been discussed by Chan (2004) and to some extent Boussu et al. (2002) and Forman et al. (2007), alluding to certain weaving parameters. These parameters are often inappropriate for use in the current investigation, as they relate to fancy yarns or carbon fibre of greater diameter than the yarns used in this study. For this reason, the studies in phase 2 serve as a foundation to the later studies and focus on design rather than functional attributes. With the exception of a small number of samples in study iii, subjective methods are used for the evaluation of samples in phase 2.

4.1.1 Phase 2, study i: Visual and tactile evaluation of NiTi weavability

Focus:

Weavability

- Yarn
- Sett of fabric
- Woven structure
- NiTi
- Handle

Evaluation:

- Visual
- Tactile

4.1.1.1 Aims and methods

Starting under the premise of producing a light to medium weight fabric, maximizing usability for apparel and medical applications, the aim of the first study in phase two was to evaluate the weavability of SE 100µm and 150µm NiTi SMA wires, trained to a 20mm diameter coil. These wires would be integrated into suitable, different woven structures and the subsequent effect on the fabric's handle would be assessed. Trained wires were chosen to make initial assessments of the behaviour and shape transfer from the wire to the fabric, and also as a means of highlighting movement of the wire within the structures. Previous investigations have described twisting and the breaking out of the wire from the structure (Boussu, Bailleul et al. 2002; Chan Vili 2004). Following the reviews of materials and methods in phase 1, a number of individual variables were evaluated separately in samples using plain weave, 2/2 twill, and the combined plain weave and 2/2 twill structure discussed in section 3.2.3.4.

Key aims and evaluations of this study were:

- 2/60cc and 2/40cc mercerised cotton evenly sett in plain weave (s1-7, 14-16)
- Oversetting the 2/40cc mercerised cotton warp at 72epi, 120epi and 168epi (Table 25) to cover and enclose the integrated wire (s5-7and 14-29)
- Using viscose weft yarn with mercerised cotton warp (s8-13)
- Using polyester yarn in the warp and weft (s30-35)
- Transfer of shape from the trained NiTi wire to supporting structure (s1-35)
- Weavability and handle of the fabrics (s1-35)

Yarn	Yarn count	Yarn Ø µm *	epi[†]	Plain weave % sett	2/2 Twill % sett
Mercerised cotton	2/60cc	166	84	101	77
	2/40cc	203	72	106	80
			120	176	135
			168	247	189
Polyester	40tex	238	112	201	

*Calculated using Equation 2

[†]Calculated using Brierley's theory of empirical maximum weavability

Table 25 The percentage of full sett for the samples used in phase 2, study i.

4.1.1.2 Overviews of samples

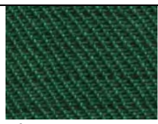
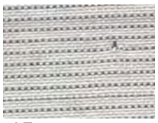
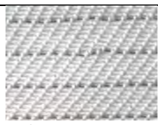
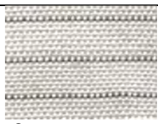
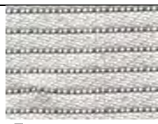
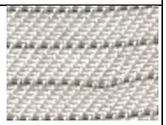
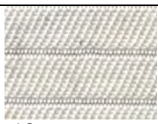
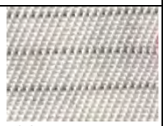
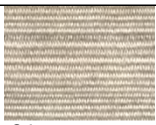
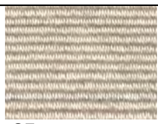
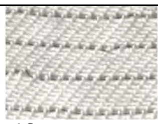
Table 26 shows an overview of samples woven in study i. For a full breakdown of the composition of the samples please refer to appendix C.

Sample	Supporting yarn	epi	Weave	NiTi wire (µm)	Sample size
1	Mercerised cotton 2/60cc	84	Plain weave & 2/2 twill	150	100x100mm
2			Plain weave & 2/2 twill	100	
3			Plain weave	100	
4			2/2 twill	100	
5	Mercerised cotton 2/40cc	72	Plain weave & 2/2 twill	150	
6			Plain weave	150	
7			2/2 twill	150	
14			Plain weave & 2/2 twill	100	
15			Plain weave	100	
16			2/2 twill	100	
17		120	Plain weave	100	50x100mm
18				150	
19			Plain weave & 2/2 twill	100	
20				150	
21			2/2 twill	100	
22				150	
23			Plain weave	100	
24		168	Plain weave	100	100x100mm
25				150	
26			2/2 twill	100	
27				150	
28			Plain weave & 2/2 twill	100	
29				150	
8	Viscose	72	Plain weave & 2/2 twill	150	
9			Plain weave	150	
10			2/2 twill	150	
11			Plain weave & 2/2 twill	100	
12			Plain weave	100	
13			2/2 twill	100	
30-35	Polyester	112	Plain weave	*a*	

Table 26 Overview of samples produced in phase 2, study i.

4.1.1.3 Results

The results concentrate on the seven key aspects relating to the integration of NiTi wires into woven structures stated in the aims and methods of this study. Table 27 shows close up images of the samples produced in this study (for full details and images please refer to appendix C.). The samples in this table have been arranged to make the comparison of variables between samples easier, than would a numerical structure.

		100µm			150µm		
		Plain weave	Plain and 2/2T	2/2 twill	Plain weave	Plain and 2/2T	2/2 twill
2/60cc mercerised cotton	84e epi					 s1	
	84e pi	 s3	 s2	 s4			
2/40cc mercerised cotton	72 epi	 s14  s15		 s16	 s6	 s5	 s7
	120 epi	 s17	 s19	 s21	 s18	 s20	 s22
	168 epi	 s24	 s28	 s26	 s25	 s29	 s27
240cc Viscose	72 epi	 s12	 s11	 s13		 s8	

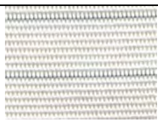
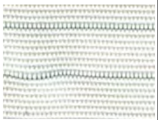
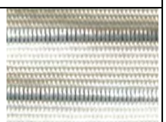
		Plain weave					
		All polyester	100µm	115µm	150µm	25x445µm	170x900µm
2/40cc Polyester	120 epi	 s30	 s31	 s32	 s33b  s33c	 s34	 s35b  s35c
Scale cm							

Table 27 Samples woven as part of phase 2, study i. (NiTi components can be seen as dark wires and ribbons running horizontally in the weft) (original in colour).

2/60cc and 2/40cc mercerised cotton evenly sett in plain weave (s1-7, 14-16)

The use of 2/60cc mercerised cotton produced very fine fabric which resulted in distortions in the weave and the breaking out of the wire from the structure (Table 27 s1). It became apparent during the weaving of sample 1 that although a viable sample could be produced, great care was required during insertion of the wire into the structure due to its dominance. This dominance is a result of the similarity between the diameters of the supporting cotton (which using Equation 1 was calculated at 166µmØ) and the wire, combined with the mechanical differences between a spun yarn and single component wire. The integration of the 100µm wire into samples woven using a 2/40cc mercerised cotton (s2-4) was more appropriate for the weight of the supporting yarn, producing less disruption to the fabric's hand and subsequently a smoother, more even fabric (Table 27 s2-4). Weaving difficulties still remained and subsequent samples (s5-7 and s14-16) used a the slightly heavier 2/40cc mercerised cotton yarn, improved both the coverage and integration of the 100µm wire (s14-16) and 150µm wire (s5-7). The resulting samples were less dominated by the wire and as such were more suitable for apparel fabrics or close contact with the skin. The decision was made at this early stage to use a 2/40cc mercerised cotton as the basic yarn throughout the investigation as it would provide a suitable structure for the wider range of wires and ribbons planned for the investigation. In addition the selection of a single cotton yarn type would remove one of the variables, thereby making the comparison between samples easier.

Oversetting the 2/40cc warp at 72epi, 120epi and 168epi to cover wire (s5-7 and 14-29)

Samples s5-7 and 14-29 investigated the effects of over-setting fabrics using 2/40cc mercerised cotton warps, containing both 100µm and 150µm wires (Table 27). Starting with samples sett at 72epi (s5-7 and 14-16) woven in plain weave, 2/2 twill and the combined plain weave and 2/2 twill structure, the investigation continued with samples sett at 120epi (s17-23) and 168epi (s23-29).

As discussed in the previous section, although it was still necessary to take care during the insertion of the NiTi wire, samples s5-7 and 14-16 generally produced acceptable samples. Both the 100µm and 150µm wire were still dominant in the woven structure, being very visible, although not dramatically distorting the surface of the fabric. The weaving defects were most noticeable in the 2/2 twill samples (s7 and 16) where due to the looser weave the wires were able to move relatively freely in the structure (Table 27). This became much less evident in plain weave samples which produced a crisper and very stable fabric, although as can be seen in s15 (Table 27), due to the spring and coil training of the wire, tight loops broke out of the structure. The combined weave samples, although looser and exhibiting more distortion than the plain weave samples, maintained much better stability and integrity when compared to the 2/2 twill samples (Table 27).

Samples 17 – 23 were woven at 120epi, resulting in a 2/2 twill to be over sett by 143.427%. These samples demonstrate an improvement in the woven structures and consequently, the integration of both the 100µm and 150µm wires. Although the 2/2 twill samples (s21 and 22) were still looser than the plain weave samples (s17 and 18), there was much less movement of the wire in the structure (Table 27). However there was increased distortion of the structure in s20, which integrated the 150µm wire into the combined weave when compared to s19 using the 100µm wire

(Table 27). In the plain weave (s17, 18) and 2/2 twill (s21, 22) samples, the wires were still very visible in the structures, causing very little surface distortion. The visual impact of the wire was much reduced in the combined sample being almost continually covered by the warp threads.

The third set of samples (s24 - 29) were substantially over sett at 168epi, resulting in the 2/2 twill being over sett by 202.772%. Visually, these samples exhibited very good insertion of the 100µm and 150µm wire into the structure, resulting in very even fabrics, with the wires being almost completely covered by the warp threads in all the samples. The stability of the 2/2 twill (s26-27) and combined weave samples (s28, 29) was much improved when compared to the sample woven at 120epi. Although the wires integrated well into the plain weave structure, the integrity of the samples had been compromised by the increase in epi. With this increase, there was a corresponding reduction in picks per inch, reducing the tightness of the structure as it became ribbed and weft faced. This ribbing can be seen in the plain weave samples s24 and s25, together with the corresponding loss of integrity, as demonstrated by the gentle manipulation of the over sett cloth (Table 27). At 168epi, the 2/2 twill and combined weave samples s26-29 still maintained their integrity.

Using viscose weft yarn with mercerised cotton warp (s8-13)

In comparison to the previous samples, samples s8 and s11-13 were woven using a 2/40cc viscose in the weft. The samples were very disappointing with even the plain weave sample s12 (Table 27) showing a large amount of movement and twisting of the wire in the structure as well as general weaving defects (Table 27). Although the viscose used had the same yarn count as the cotton it was a slightly finer yarn and due to the smoother fibres resulted in a looser woven structure. Further investigation is needed to better understand the behaviour of viscose yarn in NiTi composite structures.

Using polyester yarn in the warp and weft (s30-35)

Polyester samples were designed to emulate the structure seen in a cardiovascular stent supplied by Tony Anson (Table 27). The function of this kind of stent is to limit the migration of blood, and as such, it uses a dense weave. In contrast to the viscose sample, the polyester samples s30-35 demonstrated much better weavability and integration of the NiTi wires. The polyester yarn was a two - fold yarn with a tex count of 40. Using a yarn of this count was comparable to a yarn with a cotton count of 2/30cc. The polyester was Sett at 112epi, which is approximately 200% sett, meaning it fell between the 120epi (s17-23) and 168epi (s124-129) range of the mercerised cotton samples. Being over sett to this extent resulted in some weft ribbing, although the samples did not lose their integrity, and controlled the NiTi wire with very few weaving defects.

A second element to the weaving of the polyester samples was the first insertion of 115µm wire as well as 25µm x 445µm and 170µm x 900 µm NiTi ribbons. The weavability of the 115µm wire was much the same as the 100µm and 150µm wires already used. The fineness of the 25µm x 445µm ribbon initially made weaving slow, as twisting within the woven structure had to be avoided. After some practice, it was found that if a light tension was held on the wire during the initial beating down of the weft, twisting was greatly reduced.

Until s35, the samples produced had used a continuous wire, which would aid resistive heat setting and activation. This method worked well, with the exception of a few samples where the combination of a loose structure and insufficient slack being afforded in the returning of the wire caused the edges of the cloth to distort (Table 27). The introduction of the springy and more substantial 170µm x 900µm NiTi ribbon in s35b resulted in extensive distortion to the sample (Table 27). To correct this and produce a viable cloth, the decision was made to insert the 170µm x 900µm NiTi ribbons as individual lengths (Table 27). This set up would require either the individual connection of the wires for resistive heating or the use of simple, pre-programmed forms like arcs. The removal of the 170µm x 900µm NiTi ribbon from the plain polyester structure in sample s35c was very easy, with the structure offering little resistance to the extraction of the wire.

Shape transfer from the NiTi component to the woven structure

The samples produced in phase 2, study i, have provided a clear indication of the levels of control that are attainable in an active textile through the integration of a trained NiTi wire and the manipulation of the woven structure (Figure 52). The samples produced demonstrated varying degrees of shape transfer, from minimal in samples like s8, through varying degrees of curvature seen in s5 and 11, to the very close reproduction of the trained 20mmØ coil in sample 15. As well as these controlled even forms, more erratic shape transfers were seen in s7, 8 and 16, as the NiTi wire twisted in the structure.

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Figure 52 Effect the woven structure can have on the transfer of shape from similarly trained NiTi wires (original in colour).

At this initial stage, the shape transfer appeared to be following two trends which centred on the number of warp ends and intersections in contact with the wire. As these increased, whether as a result of the weave used (plain weave having two ends and two intersections in one repeat, compared to 2/2 twill that has four ends and two intersections in one repeat) or the setting of the fabric, greater control was transferred, resulting in a tighter curvature closely resembling the trained diameter of the wires. If the interlacement between the SMA and supporting textile is reduced and offers too much freedom of movement, the shape transfer from the wire to the textile will be reduced and a more open arc is formed. In looser structures, notably in samples s7, 8 and 16, the samples formed 'S' shapes rather than a single arc. This double curvature was a result of the inserted wire twisting in the structure and creating unpredictable distorted forms.

The results of this study were contrary to the prediction of Chan (2004) who discussed a reduction in shape transfer in higher sett fabrics due to restriction of the shape memory effect. This study has demonstrated that in samples that remained lightweight, the increased epi and tightness (s15, 23 and 24) supported the shape transfer, whereas in an under sett 2/2 twill fabric (s7, 21 and 26) the wire is able to move freely within the structure, reducing the shape transfer from the wire. The larger number of contact points between the wire and the perpendicular warp threads, as a result of an over-sett fabric, increases the control and integration of the wire in the structure. The limitations of this method of promoting shape transfer are evident in samples sett at 168 epi. At this level of over setting two factors were evident that hindered shape transfer. The first of these was the increased weight and bulk of the fabric due to the number of warp threads, but more critically the increase in epi results in a corresponding reduction in weft threads per inch. This decrease in weft ends reduces the tightness and integrity of the cloth and its ability to restrain the integrated wire.

The NiTi wire volume fraction was investigated in samples 14 - 15 and samples 17 and 23. Both sets were woven in plain weave, mercerised cotton; the first set was woven at 72 epi, the second at 120 epi. For samples 15 and 23, the NiTi was inserted on every fourth pick, whereas for samples s14 and 17 the NiTi was inserted on every eighth pick; all other parameters for the samples remained the same. A marked difference was seen in the transferred curvature between the samples with s14 and 17 showing a gentle curvature, as opposed to s15 and 23, which produced a tight curl comparable in diameter to the shape of the original trained wire. Samples 15 and 23 showed no reduction in the sample integrity, due to the increased NiTi present.

Weavability and insertion of wire into the woven structures

The samples produced in phase 2, study i, demonstrated good weavability in spite of the springy nature of the trained wire. Care had to be taken when inserting the NiTi wires to keep weaving defects to a minimum. However, there were signs of wires breaking out of the textile, and distorting the supporting fibres but this was more noticeable in the lower set cloth. In the earlier undersett plain weave samples s6 and 12 (Table 27), it was noted that puckering was occurring during weaving. This was caused by insufficient free wire for the return to accommodate the tightness of the plain weave. In later samples, this was alleviated by ensuring enough free wire was available at the return end. For all samples the main compatibility issue with the integration of any wire into a very flexible and adaptable structure, such as textiles, is exceeding the wire's minimum bend radius. When the bend radius is exceeded, a permanent buckling of the wire component forms a fault line or fold in the textile.

Handle of the fabrics

The handle of the samples is closely related to the trained shape of the NiTi wire and the shape transfer to the fabric. In the current samples, because the inserted wire was superelastic, the influence was constant. As a result of its inherent elastic properties, it was difficult to evaluate the effect an inactive thermal shape memory wire would have on the woven structure. Despite the obvious influence of the superelastic effects, the handle of the fabric was favourable, with the fine NiTi wires integrating well within the structure.

4.1.1.4 Summary of results for phase 2, study i

The samples produced in this study have successfully laid the foundation and provided a range of basic parameters and key influences for the successful production of woven samples integrated with NiTi components.

Based on the aims stated at the beginning of this study the main conclusions are as follows:

- Although acceptable samples could be produced combining the 2/60cc yarn structure with a 150µm wire, this was at the upper limit, with the wire becoming very dominant proportionally to lighter fabric. The use of the heavier 2/40cc yarn structure offered scope for greater versatility and was subsequently used as a basis for later samples.
- It has been demonstrated that by increasing the epi and over setting the cloth, the weavability of the NiTi improved, as well as the covering of the wire. Although oversetting a cloth can increase stability, this has a limit; beyond a point, the reduction in picks dramatically reduces the stability of the structure resulting in a reduction in the control of the NiTi component.
- Initial investigations into the use of alternative supporting yarns were mixed. The polyester samples produced were stable and of good quality whereas the viscose samples, although directly comparable to the mercerised cotton samples, produced very disappointing results. The viscose samples were very loose, offering little resistance to movement by the NiTi in the structure. As viscose does not offer any specific technical or design advantages over the other yarns chosen, it was not considered for use in further sampling within the scope of this investigation.
- The transfer of shape from the NiTi component to the woven structures was very positive, with a wide range of variety being demonstrated. The variety in transferred shape ranged from almost total in the lighter, tighter structures, to minimal in the heavier or looser structured samples. This range of potential shape transfer can be utilised for the creation of direct and indirect shape transfer.

- This study has shown that through manipulation of variables, the weavability of NiTi samples can be improved, offering scope for the continued development of woven NiTi composite samples. The handle of the resulting samples can also be manipulated to the extent that the integrated NiTi components have a limited effect on the sample, either visually or in tactile terms resulting in the possible production of a broad range of weights of cloth suitable for a variety of applications.

As a result of the successful outcomes from this study, parameters such as the sett of the fabric and composition of the supporting yarn are investigated in more focused studies in phase 3 (study i and studies ii and iii respectively).

4.1.2 Phase 2, study ii: Introduction of selvedges to cover wire ends

Focus
Weavability

- Balancing the cloth to accommodate the selvedge and NiTi in the body of the cloth
- Weavability
- Handle

Evaluation:

- Visual
- Tactile

4.1.2.1 Aims and method

The aims of this study concern the practical design of NiTi composites rather than the interaction between the NiTi wire and supporting structure, so they are an addition to the initial investigation. As such, the samples in this section have been woven, mainly as a point for future reference rather than for specific analysis, although with the introduction of untrained wires, some comparisons can be made regarding the handle of the fabrics while not under the influence of the shape memory effect.

While weaving the samples in phase 2, study i, the exposed nature of the NiTi wires on either edge of the fabric became apparent; methods of limiting this exposure were considered that were integral to the sample. The method adopted was in keeping with a later, planned study (now phase 2, study iii), which involved the weaving of selvedges at the edges of the main body of the cloth, that could be folded over the exposed wires and stitched to conceal them. The addition of a selvedge to the main body of the sample can cause an imbalance to the fabric as a whole for two reasons. First, an imbalance becomes apparent when the woven structure of the body of the fabric and the selvedge are different, as can be seen in samples s50-56, which combine a plain woven selvedge and the main body of the sample, a 2/2 twill. The second reason for an imbalance is the is the insertion of a NiTi component. In both cases small differences can be accommodated in the overall structure. However, if there is a greater difference, in particular with the insertion of a large wire, an imbalance can occur, which needs to be corrected by the inclusion of additional weft picks to balance the overall structure. The main body of the samples woven in this study consisted of either plain weave, 2/2 twill or the combined woven structure, with selvedges in either plain weave or 2/2 twill. Although the samples in phase 2, study ii, are over sett and as such have a naturally stiffer handle than many of the samples in study i, they do allow an insight into the effects the integration of an active and inactive NiTi element would have on the fabric's handle.

4.1.2.2 Overview of samples

Not all the samples listed were woven, due to limited amounts of wire. For each combination of woven structure both the 25 x 445µm and 170 x 900µm NiTi ribbons were used as they would demonstrate the greater impact and imbalance given their increased dimensions. For this reason samples with one or two additional picks were woven in the selvedge to balance the cloth. Based on the results of phase 2, study i, all the samples in study ii were sett at 144 epi to provide good coverage of the integrated SMA wires without the problems seen in samples s24 and s25 occurring, with the resulting lost of structural integrity (Table 28).

Yarn	Yarn count	Yarn Ø µm *	epi†	Plain weave % sett	2/2 Twill % sett
Mercerised cotton	2/40cc	203	120	176	135
			144	212	161
			168	247	189

*Calculated using equation 2
†Calculated using Brierley's theory of empirical maximum weavability

Table 28 Percentage of over setting investigated in the mercerised cotton samples.

Table 29 shows the breakdown of samples woven for phase 2, study ii. For full details of the composition and production of the samples please refer to appendix C.

					Additional weft thread in selvedge								
					1						2		
Sample	Supporting yarn	epi	Set of sample	Weave	Cotton	100µm	115µm	150µm	25x445µm	170x900 µm	25x445 µm	170x900 µm	Sample size
37-43	Mercerised cotton	144	1	PW - PW selvedge	X	X	X	X	X	X	X	X	100 x 100 mm
44-49			2	2/2 twill - twill selvedge	X	X	X	X	X	X	X		
50-56			3	2/2 twill - PW selvedge			X		X	X	X	X	
57-61			4	PW, 2/2 twill – PW, 2/2 twill selvedge			X		X	X			
62-66											X	X	
67-72			5	PW, 2/2 twill – PW selvedge	X	X	X	X	X				
73-77											X	X	

Table 29 Overview of samples produced in phase 2, study ii.

4.1.2.3 Results

The results concentrate on the three aims stated at the beginning of this section. Close up images of the transition between the selvedge and body of the sample with the integrated NiTi component can be seen in Table 30.

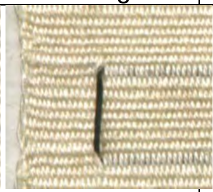
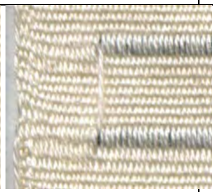
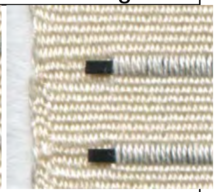
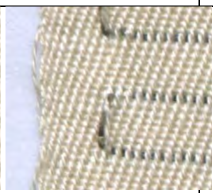
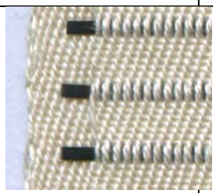
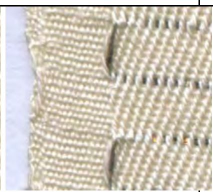
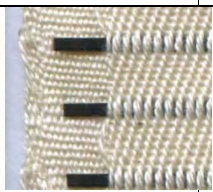
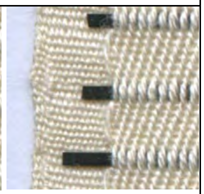
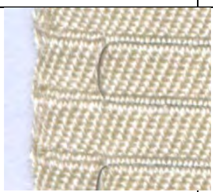
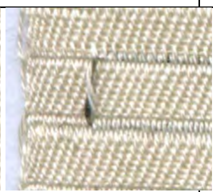
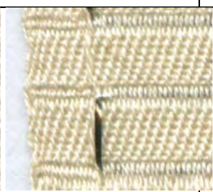
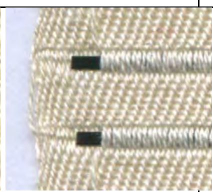
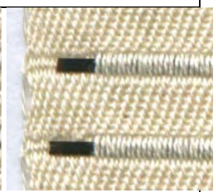
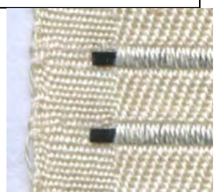
	115 µm	25x445µm	25x445µm With additional weft thread in selvedge	170x900µm	170x900µm With additional weft thread in selvedge
PW, body PW selvedge	 s40	 s42	 s42b	 s43	 s43b
2/2 twill body 2/2 twill selvedge	 s46	 s48		 s49	
2/2 twill body PW selvedge	 s51	 s53	 s55	 s54	 s56
PW, 2/2 twill body PW, 2/2twill selvedge	 s58	 s60	 s65	 s61	 s66
PW, 2/2 twill body PW selvedge	 s69	 s71	 s76		 s77
Scale cm					

Table 30 Samples woven as part of phase 2, study ii (NiTi components can be seen as dark wires and ribbons running horizontally in the weft) (original in colour).

Balancing the cloth to accommodate the NiTi in the body of the cloth

Overall, the samples produced in this study were a success with the round wires integrating well within the structure, requiring only one additional weft pick to equalise the insertion of the wire and transition of the woven structure from the body of the samples to the selvedges. The smooth integration of the wire and balancing of the selvedge was due to the mercerised cotton having a diameter equivalent to 203µm, both greater and more adaptable than the inserted wires. These factors facilitated the accommodation of the slight differences caused by the integration of the NiTi. The 25x445µm and 170x900µm NiTi ribbons, with a flat face that was over twice and four times the diameter of the mercerised cotton respectively, created a distortion too great for a single equalising yarn to accommodate. For this reason, additional samples were woven incorporating two equalising weft yarns to balance the cloth.

The first set of samples in Table 30, samples 40 to 43, show the continuation of the plain weave body into the selvedge. In s42, the integration of the wire had little effect on the balance of the cloth but some distortion could be seen as the NiTi wire both left and re-entered the fabric. Samples s42 and s43, with the integrated ribbon, showed signs of a looser structure in the selvedge, around the insertion point of the ribbon. This is greater in s43, where there was a clear lengthening of the warp floats around the ribbon. Samples s42b and s43b incorporated two weft picks in the selvedge to compensate for the ribbon; and in sample s43b in particular the length of the warp floats was dramatically reduced.

The transition from the 2/2 twill, in both the selvedge and body of the sample, showed minimal distortion around the inserted NiTi ribbon and was able to accommodate the ribbon without an additional weft thread in the selvedge. This was a result of the looser and more accommodating structure of the 2/2 twill. The ability of the 2/2 twill to accommodate occasional increases in the dimensions of the inserted component can be seen in the next set of samples, s51 – 56, which combine a plain weave selvedge with a 2/2 twill body. As a result of the increased tightness of the plain weave structure, combined with the looser 2/2 twill the addition of a second weft pick in sample s55 shows over-packing and is less balanced than s53. The considerable difference in profile between the mercerised cotton threads and the 170x900µm NiTi ribbon meant the plain weave selvedge in s56 could accommodate the additional weft thread, thus producing a better cloth than s54.

The final two sets of samples used the combined plain weave and 2/2 twill structure in the body of the sample. The first continued this structure into the selvedge, whereas the second sample changed to a plain weave structure for the selvedge. With the looser structure of the 2/2 twill extending into the selvedge, the sample coped well with the integration of the 25x445µm NiTi ribbons, both with and without the additional weft thread. Sample s61 showed an increase in the length of the warp floats at the insertion point of the 170x900µm ribbon but these were reduced with the additional weft thread in s66, where a balanced cloth was produced. The combination of a predominantly 2/2 twill body and plain weave selvedge in s76 again demonstrates similar characteristics to s55, with some over-packing in the selvedge when a second weft thread was inserted. This resulted in s71 producing a more balanced cloth.

Weavability of the NiTi

The decision to sett the fabric at 144epi was successful as good quality samples were produced in all the woven structures. Although some ribbing was seen in the plain weave sample due to being over sett, they maintained their structure and did not lose continuity like s24 and 25. The introduction of a 115µm untrained NiTi wire was successful, integrating well without any weaving defects. It was noted that as the wire was untrained it demonstrated less spring than the trained 100µm superelastic wires previously used, and as such, improved the weavability, thereby further reducing the chances of weaving defects. The samples containing the 25x445µm ribbon showed significant distortion, a result of the fineness of the ribbon, which at 25µm thick was one quarter of even the finest wire, and as such was readily distorted, conforming to the crimp of the woven structure. The continuity of the integration was further hindered by the inability of the wire to expand, contract and distort in the same way as a spun yarn during the weaving process. As a result of the distortion caused by the fineness of the 25x445µm ribbon, a slightly thicker ribbon was sought and in future studies a 50x420µm ribbon was also used.

Handle

Acting as a control, sample s37 demonstrated the handle of the plain weave cloth without an integrated wire, s44 demonstrated the 2/2 twill cloth, and s67 the combined cloth. These samples had a soft, slightly stiff handle as a result of being over sett, with the plain weave sample, s37, being slightly crisper than the other two samples. It was also noted that although sample s67 was predominantly 2/2 twill, the inclusion of the lines of plain weave gave the resulting fabric a noticeably lighter handle than the solid 2/2 twill sample. The integration of the 115µm wire and 25x445µm ribbon had little effect on the handle of the samples. Some influence could be perceived in the handle of samples with an integrated 150µm wire but this was minimal. The integration of the larger, springy 170x900µm NiTi ribbon had a substantial effect, dominated the resulting handle of the samples. Although the 170x900µm ribbon was dominant, demonstrating a strong elastic recovery, after deformation, the ribbon did allow free manipulation and distortion of the samples whilst under pressure.

Transfer of shape from the trained NiTi wire to the woven structure

Although not one of the aims of this study it should be noted that the samples woven with the pre-trained 100µm and 150µm wire demonstrated a strong transfer of shape from the wire to the structure by producing a tight even curvature along the weft.

4.1.2.4 Summary of results for phase 2, study ii

This study has successfully demonstrated an integrated method of covering the exposed sections of the NiTi components as they travel up the warp for their next insertion.

The following are the key points that emerged from this study:

- Requiring only one equalising pick, the larger and more adaptable nature of the 2/40cc mercerised cotton, when compared to the wires, assisted in balancing the transition between the additional selvedge and body of the sample with integrated NiTi components. The balancing of samples with comparatively large, integrated ribbons was also successful but required the addition of two picks.
- The weavability of the NiTi component in the oversett cloth was good, although because of the fineness of the 25x445µm ribbon, problems were experienced during weaving and significant distortion was caused to the sample.
- The direct comparisons of samples, both with and without integrated NiTi components, showed that the finer 115µm wire and 25x445µm ribbon had a limited effect on the handle of the samples. The 150µm wire demonstrated a noticeable influence on the sample's handle, while the 170x900µm ribbon demonstrated a more dominant influence, although this, in part, was a result of its *as drawn* state.

4.1.3 Phase 2, study iii, secondary control of inserted NiTi components

Focus

Woven structures:

- o Selvedges
- o Double cloth
- o NiTi

Evaluation

Tensile test:

- o Basic mass extraction

4.1.3.1 Aims and method

Following the additional sample woven as phase 2, study ii, study iii continues the development and use of selvedges. The use of selvedges or bands of differing woven structures running in the warp direction perpendicular to the inserted NiTi wire, allows a secondary level of control to be developed and utilised. When combined with a tight selvedge acting as an anchor for a NiTi component, a double cloth structure can create a pocket, thus allowing the NiTi component freedom of movement unhindered by direct integration into the structure, having the ability to affect a large range of movements. The increased scope for movement resulting from the use of double cloth is similar to that for the externally mounted wires in rigid composites investigated by Chaudhry and Rogers (1991) discussed in section 2.5.2.3.

Key aims of this study were:

- To evaluate combinations and transition of woven structures and the sett of the cloth, from the selvedge to the body of the cloth, including double cloth.
- Initial evaluation of tensile testing to first movement and full extraction.
- The influence the epi has on the crimping of NiTi components.
- The effect that altering the woven structure and sett of a fabric has on the force required to extract an integrated NiTi component.

4.1.3.2 Overview of samples

Based on the results of phase 2, studies i and ii, all the samples in study iii were sett to have a 72 epi selvedge, providing a tight, holding structure round the inserted NiTi component together with a combination of 72 and 144 epi in the body of the sample to either allow free movement of the NiTi or to restrict it (Table 31).

Yarn	Yarn count	Yarn Ø µm *	epi[†]	Plain weave % sett	2/2 twill % sett
Mercerised cotton	2/40cc	203	72	106	80
			144	212	161

Table 31 Percentage of over and under setting investigated for mercerised cotton samples in phase 2, study iii.

For the first part of this study, seven 100mm x 100mm samples were woven which explored different combinations of woven structure and sett for the body of the cloth (Table 32). As part of the study, double cloth pockets were explored in samples s79, 82 and 114 to investigate structures that include enclosed areas within which an integrated NiTi component could move freely'?
. Informed by the results of these samples, six different weave and sett combinations were selected for the second part of this study which involved initial evaluations using the basic mass extraction method described in section 3.2.9.2.2. The individual samples were woven, integrating 115µm, 152µm, 25x445µm, 50x420µm, 170x900µm NiTi wires into each of the selected structures, thus producing samples 88-112 (Table 32). The six sets of samples were woven at 100mm x 30mm, from which two 50mm x 30mm samples were cut prior to the extraction of the wire. This size and format of sample became a standard for future evaluations, aiding comparison between sample sets.

Samples		Supporting yarn	Selvedge		Body	
100 x 100 mm	50 x 30 mm		epi	Weave	epi	Weave
78	83-87	Mercerised cotton	72	Plain weave	144	Plain weave
	88-92				72	
79	-				144 & 72 for DC	Plain weave DC
81	93-97				144	2/2 twill
113	98-102				144 & 72 for plain weave	2/2 twill, plain weave
80	103-107				144	2/2 twill, plain weave
114	108-112					2/2 twill, plain weave DC
82	-					

DC Double cloth

Table 32 Overview of samples produced in phase 2, study iii (for full details of the composition and production of the samples please refer to appendix C.).

4.1.3.3 Results for part one

Part one of this study investigates the first aim through the production and assessment of samples s78 – 82, s113 and s114 (Table 33).

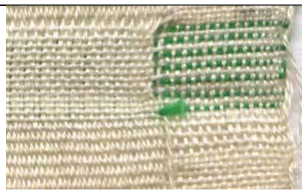
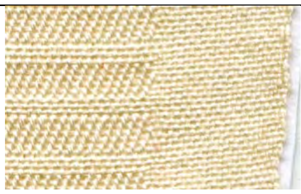
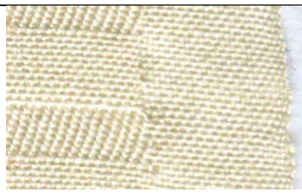
Plain weave body Plain weave selvedge (s79 is a double cloth)	 s78	 s79 Double cloth
2/2 twill body Plain weave selvedge	 s81	
Plain weave, 2/2 twill body Plain weave selvedge	 s113	 s80
Plain weave, 2/2 twill body Plain weave selvedge Double cloth	 s114 Double cloth	 s82 Double cloth
Scale cm		

Table 33 Samples woven as part of phase 2, study iii (original in colour).

The effect of a variety of combinations on the transition of the woven structure and ends per inch, from the selvedge to the body of the cloth, including the production of double cloths

The transition from plain weave sett at 72 epi in the selvedge, to 144 epi in the body of the sample, was investigated in s78 and 79. In sample 78, this was a straight transition, requiring the addition of two picks in the selvedge to keep the cloth balanced (appendix C). Sample 79 investigated the same transition from 72epi to 144epi but with the inclusion of bands of double cloth in the body with faces each of 72epi. These samples again required an additional two picks in the selvedge when corresponding to the 144epi bands; however, because the epi was the across the sample in the double cloth bands, no additional picks were required. The production of this sample was successful, although banding could be seen as the yarn in the selvedge tried to accommodate the changes in the body of the sample, while the additional picks need to be placed more evenly through the repeat. Samples 81 and 82 considered the same forms of transition but 144epi 2/2 twill was used instead. The looser structure of the 2/2 twill meant it could accommodate the additional ends in the warp without the need for additional picks in the selvedge to keep the cloth balanced. The double cloth and 2/2 twill sample, 82, showed some banding in the selvedge but this was not as noticeable as in the plain weave sample 79. The remaining three samples, 80, 113 and 114, all looked at the transition from the 72epi plain weave selvedge to the combined plain weave and 2/2 twill structure. Sample 80 consisted of a straight transfer from the selvedge, with both woven structures in the body being sett at 144epi. This produced a balanced cloth, although it was notable that the dispersion of the selvedge picks was greater than for the other samples, as they accommodated the different structures in the body of the sample. To rectify this dispersion and to create a tighter selvedge, additional picks would be required in the selvedge. Samples 113 and 114 were very similar in structure, unlike sample 80, the plain weave sections in the body of the sample were woven at 72epi, rather than 144epi. In sample 114, the plain weave sections in the body of the sample, formed a double cloth. In a similar way to sample 79 both faces were woven at 72epi. In sample 113, only one face of the double cloth is woven and the remaining threads were left as floats on the back. Although in sample 113 the floats were short, if wider bands were woven they could be cut, thus reducing the weight of the cloth in these areas.

4.1.3.4 Summary of results for phase 2, study iii, part 1

This part of the study has demonstrated a variety of combinations in the transition of the woven structure and ends per inch, from the selvedge to the body of the cloth, including the production of double cloths. When producing these samples, the main consideration was to keep them balanced, which was achieved by increasing the number of weft picks in the selvedge to compensate for the increased epi in the body of the samples. To investigate further the changes in the structure and epi combinations, elements from samples 78, 80, 81, 113 and 114, were used as a basis for the production and testing of additional samples (Table 34). These samples were investigated in the second part of this study, and provided a range of influences across the integrated NiTi components.

	Influences on integrated NiTi components				
Sample	Selvedge		Body of sample		Samples
78	Plain weave	72 epi	Plain weave surrounded by plain weave	144epi	83-87
			Plain weave surrounded by plain weave	72epi	88-92
80			Plain weave surrounded by 2/2 twill	144epi	103-107
81			2/2 twill surrounded by 2/2 twill	144epi	93-97
113			Back threads are cut to release the wire	Free	98-102
114			Plain weave surrounded by 2/2 twill	Free in double cloth pocket	108-112

Table 34 Overview of samples produced in phase 2, study iii, part one and the relationships to the samples woven for part two.

Although in the above and the subsequent samples the transitions are discussed as being from the selvedge to body of the sample, this can be translated into any number of bands running across the weft threads. Alterations to the structure or sett of a fabric in this manner can be used to create indirect shape transfer on a number of different levels along a single integrated NiTi component. This diversity of shape transfer would be difficult to achieve in a singularly direct transfer from an inserted NiTi component to the supporting structure.

4.1.3.5 Results for part two

From the results of the first part of this study, further samples were produced and evaluated using the basic mass loading technique described in 3.2.9.2.2. These tests investigated differences in force required to dislodge and extract a selection of NiTi components from a range of woven structures. A constant throughout all the samples was the use of plain weave selvedges made up of 28 warp ends (approx 1cm), sett at 72epi, which would provide a tight structure to hold the NiTi. For the bodies of the samples, a combination of plain weave and 2/2 twill structure was used sett at 144 and 72 epi respectively (Table 35). The NiTi wire used consisted of 115µm and 152µm wires, and 25x445µm, 50x420µm and 170x900µm ribbons. With the exception of the 115µm wire, which had a pickled finish, all the NiTi samples had an oxide finish. This continuity aided the interpretation of the results, increasing the comparability between the other variables. The selection of NiTi wire samples remained constant for the remaining samples produced in phase 3, so direct correlations can be made between the results of this and subsequent studies.

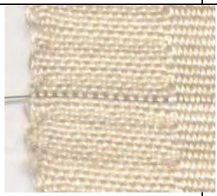
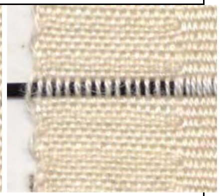
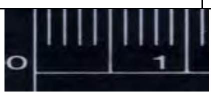
	115 µm	152µm	25x445µm With additional weft thread in selvedge	50x420µm With additional weft thread in selvedge	170x900µm With additional weft thread in selvedge
144 epi Plain weave	 S83	 S84	 S85	 S66	 S87
72 epi Plain weave	 S88	 S89	 S90	 S91	 S92
144 epi 2/2 twill	 S93	 S94	 S95	 S96	 S97
144 epi 2/2 twill 72 epi plain weave	 S98	 S99	 S100	 S101	 S102
144 epi 2/2 twill, plain weave	 S103	 S104	 S105	 S106	 S107
144 epi plain weave 72 epi for plain weave double cloth	 S108	 S109	 S110	 S111	 S112
Scale cm					

Table 35 Samples woven as part of phase 2, study iii (all samples have a 72epi selvedge). (NiTi components can be seen as dark wires and ribbons running horizontally in the weft) (original in colour).

Initial evaluation of tensile testing: first movement and full extraction

Part two of this study was the first to evaluate the static loading of the composite samples using the basic mass loading technique, with the forces required to dislodge and extract an integrated NiTi component from a woven structure recorded for investigation. The point at which a NiTi component is dislodged from a structure is more pertinent to the creation of accurate, controlled patterns of movement than the maximum forces required for full extraction. To equate this to the integration of NiTi components within a polymer matrix, following initial release, continuity along the length of the wire is lost, with a failure in the integrity of the structure recordable, even if the majority of the wire is still intact within the structure.

The results in Table 36 show that full extraction of the integrated element was usually equal to the first movement in the supporting structure. The exception to this can be seen in samples 85, 95, 105, and 110, which all had the 25x445µm ribbon as the extracted element. During the extraction testing of these samples, it was noted that instead of releasing in one smooth movement the extraction was staggered as a result of the un-crimping of the ribbon from the woven structure. After the removal of the wire from the samples, the crimping could be seen in the wires from sample 110 (Figure 53 a) whereas the ribbons extracted from samples 90 and 105, which were extracted smoothly, show limited signs of crimping (Figure 53 b).

Sample number	NiTi component	Extraction load to first movement (g)	Extraction load for removal (g)	Difference
83	115 µm	106.2	106.2	-
84	152 µm	59.2	59.2	
85	25x445 µm	86.8	160.4	74
86	50x420 µm	53.8	53.8	-
87	170x900 µm	58.1	58.1	-
88	115 µm	115.6	115.6	-
89	152 µm	62.9	62.9	-
90	25x445 µm	144.5	144.5	-
91	50x420 µm	56.8	56.8	-
92	170x900 µm	46.8	46.8	-
93	115 µm	70.9	70.9	-
94	152 µm	47.8	47.8	-
95	25x445 µm	127.2	172.2	45
96	50x420 µm	313.4	313.4	-
97	170x900 µm	38.6	38.6	-
98	115 µm	64.3	64.3	-
99	152 µm	45.6	45.6	-
100	25x445 µm	75.1	75.1	-
101	50x420 µm	46.6	46.5	-
102	170x900 µm	61.1	61.1	-
103	115 µm	128.3	128.3	-
104	152 µm	77.6	77.6	-
105	25x445 µm	168.8	239.2	70
106	50x420 µm	68.7	68.7	-
107	170x900 µm	42.9	42.9	-
108	115 µm	106.2	106.2	-
109	152 µm	66	66	-
110	25x445 µm	181.7	333.7	153
111	50x420 µm	51.3	51.3	-
112	170x900 µm	65.2	65.2	-

Table 36 Comparison of load required to initiate first movement of the NiTi in the supporting structure and full extraction.

a.

b.

Figure 53 Examples of the level of crimping seen in the extracted 25x445µm NiTi ribbon. (a) High level of crimping (b) Low level of crimping (original in colour).

The effect of altering the woven structure and sett of a fabric on the force required to extract an integrated NiTi component

The different levels of crimping seen on the 25x445µm ribbon indicate a complex relationship between the variables and the interactions that affect the composite structure. The results for samples 83-87 and 88-92, 144epi and 72epi plain weave respectively (Figure 54) again demonstrated that the manipulation of the sett of a fabric by increasing the epi can lower the extraction forces as the influence of the structure on the NiTi components decreases. Requiring the highest forces to initiate first movement, the NiTi components in samples 103-107 were also held in a 144epi plain weave. Instead of being surrounded by the same plain weave structure as in samples 83-87, the NiTi components in samples 103-107 were surrounded by a 2/2 twill sett at 144epi. The combination of woven structures notably increased the forces required due to the increased interlacements and subsequent surface contact of the plain weave, while the 2/2 twill alleviated the issues of oversetting the fabric. The influence of over setting a fabric when compared to changes in the woven structure, can also be seen when comparing the 2/2 twill structure, which although over sett still maintains a restrictive structure when continuity in the plain weave is lost.

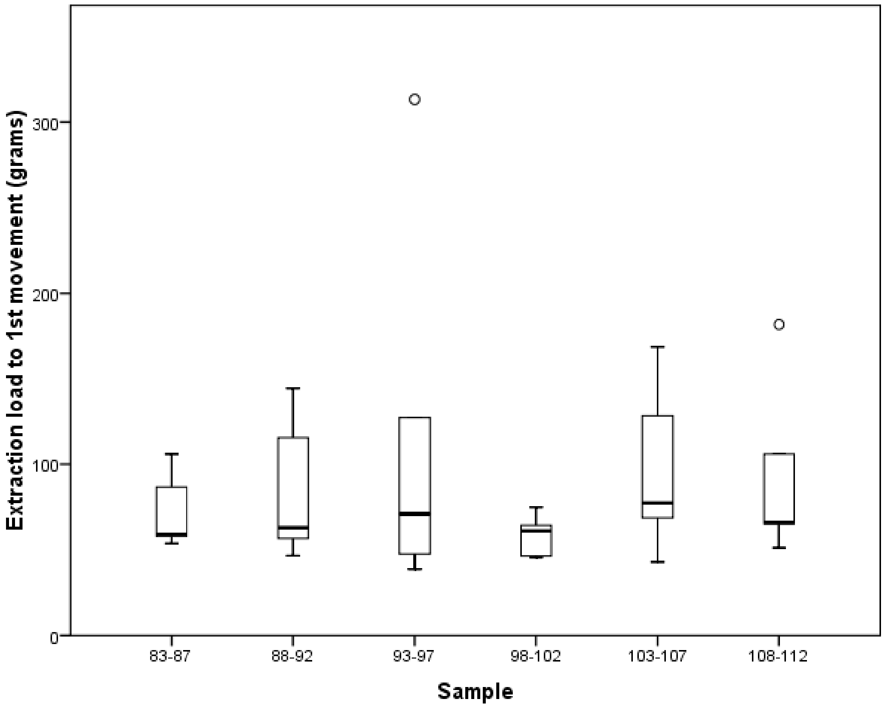


Figure 54 Effect different woven structures have on extraction load to first movement (see Figure 51 for information on the structure of the box plots).

Shown in diagrammatic form, Figure 55 represents cross sectional slices through under, evenly and over sett plain weave and 2/2 twill structures, and the relationships they have with the inserted NiTi components. The integration of NiTi components into an under sett cloth (Figure 55 a and e) causes limited distortion to the NiTi component, as it dominates the cloth and moves freely within the structure. This results in a relatively small force being required to achieve first movement and subsequent removal of the NiTi component. Increasing the epi to the point of an evenly sett cloth (Figure 55 b and f) increasingly restricts the NiTi as it is held more tightly in the structure, suffering larger distortions as a result. This structure requires increasing levels of force to remove the NiTi from the cloth. As the epi increases beyond the point of being evenly sett, the dimensions of the NiTi component progressively influence the results. Thicker NiTi components still only conform in a limited manner to the woven structure (Figure 55 c and g). Eventually, as the number of picks decreases, corresponding to the increase in epi, the warp ends start to rise on either side of the NiTi component so decreasing the force required for extraction. Conversely, the more deformable, fine NiTi components conform to the woven structure (Figure 55 d and h). With the increase in epi and interlacements, the force required to extract the fine NiTi components also increases, promoting the staggered removal seen in samples 85, 95, 105 and 110. Translating this to a 2/2 twill structure, the representations in Figure 55 e, f, g and h demonstrate that, due to the reduced number of interlacements for the same number of epi, the 2/2 twill structure has less influence on the NiTi component than the comparable plain weave.

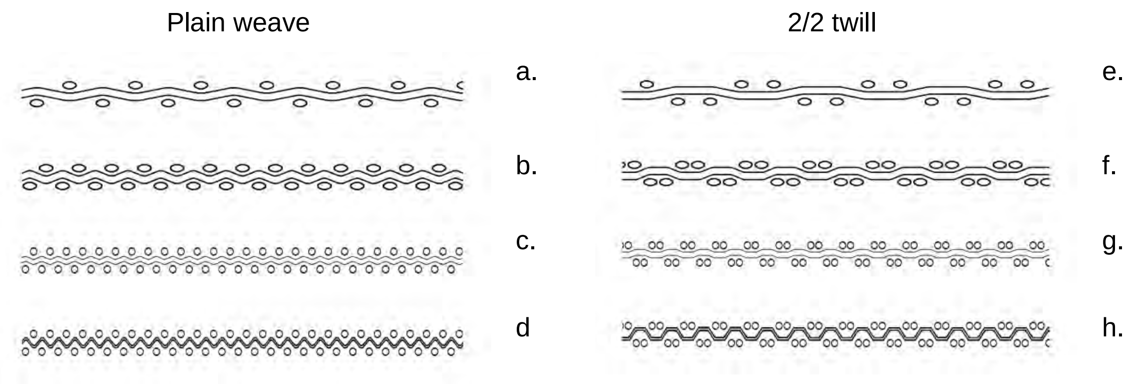


Figure 55 Diagrammatic representation of the effect that under and over setting of the woven structures has on integrated NiTi components; (a. & e.) under sett, (b. & f.) evenly sett, (c.& g.) over sett, (d. & h.) over sett with a highly formable NiTi component.

The conforming of fine NiTi components to the woven structure increased the integration of the wire, at the expense of accurate insertion due to the distortion caused to the wire. This study has shown that the impact of fine components conforming closely to the supporting structure can be either a positive or negative characteristic. Whilst the deforming of a finer component was not advantageous for accurate, direct shape transfer, the increased levels of force required to remove the component (Table 36) provided a good anchor, form which the creation of indirect or secondary levels of shape transfer could be achieved.

The effect the woven structure had on the forces required to initiate the first movement of the inserted elements can be seen in Figure 54. Acting as a baseline, the results for samples 98 – 102 clearly demonstrate the lowest forces required. As described earlier, the NiTi components in these samples had been freed from the floats in the body of the sample prior to testing, meaning that the extraction forces were only influenced by the selvedge. In a similar manner, the NiTi components in samples 108 – 112 were not directly integrated into the body of the woven structure but travelled in a narrow double cloth pocket. As demonstrated by the results in Table 36 and Figure 54 the narrow double cloth pocket in these samples exerted some influence on the 115µm and 25x445µm components, and to a lesser extent, the 152µm wire. Further investigation would be required to fully understand the influences behind these results because although the higher forces for the 25x445µm could be attributed to the compression of the fine ribbon in the narrow channel (not evident in the other, less deformable ribbons), it does not explain the outcomes for the wires.

The final part of this study was an overview of the extraction forces required to initiate first movement based on the NiTi components. Figure 56 confirms the other results in the study by clearly showing the 25x445µm ribbon and 115µm wire requiring notably more force to achieve extraction than the less deformable 152µm wire and 50x420µm ribbon, with the substantially heavier 170x900µm ribbon requiring the least force.

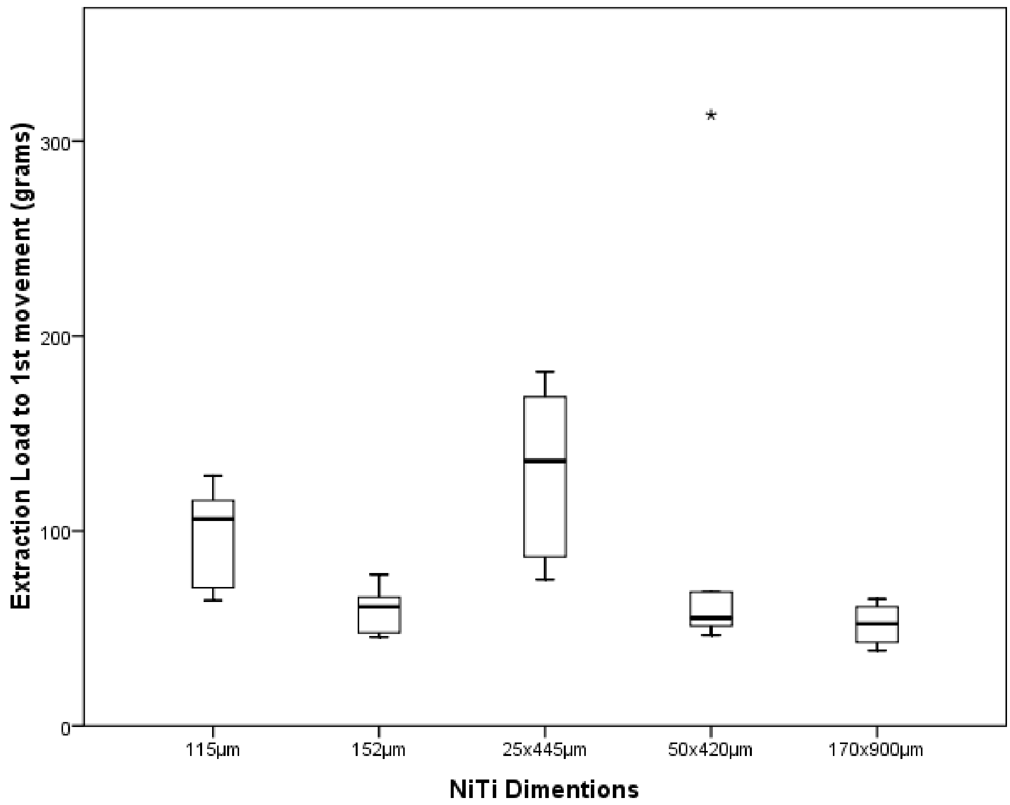


Figure 56 Effect NiTi dimensions and cross section have on extraction loads required to initiate first movement (see Figure 51 for information on the structure of the box plots).

4.1.3.6 Summary of results for phase 2, study iii, part 2

This part of the study has made initial evaluations of the basic mass loading technique, including differences in force required to initiate the first movement of the NiTi components in the structure as well as full extraction. Investigating differences in key variables, the study continued by evaluating the effect the sett and structure of the cloth, as well as the dimensions and section of the NiTi components, had on extraction forces from samples with a 72epi plain weave selvedge.

The following key points emerged from this study:

- It has been demonstrated that whilst the majority of samples required no additional force to achieve full extraction after the first movement had been initiated, a number of the finer 25x445µm ribbon samples required notable amounts of additional force as the NiTi components conformed to the crimp of the woven structure.
- The conformity of the NiTi components to the woven structure is a complex relationship that can be manipulated by varying their dimensions, the sett of the cloth and woven structure. This can be utilised for either the promotion of accurate, direct shape transfer from the NiTi component or the anchoring of it in the structure to facilitate secondary shape transfer.

Although the samples produced as part of this study consisted of a single woven structure in the body, surrounded by a selvedge on either side, this could easily be adapted to a series of differing structures in the body of the cloth, each affecting the shape transfer of the wire in different ways.

4.2 Phase 3

In phase 3, specific variables are investigated along with the degree to which they can be manipulated and used to alter the interfacial relationship, performance and potential of NiTi components to create controlled patterns of movement in woven textiles. The analysis of specific variables repeated in consistent multiple variants will start to define the boundaries and scope of controllable NiTi composite textiles. Due to the complexities of modelling NiTi, textile composite structures, and the finite results this would supply, empirical testing and evaluation methods were used to show whether the samples could demonstrate the significant diversity of performance required for the creation of a secondary level of control.

The evaluation of samples in phase 3 predominantly used objective methods, in the form of bend testing, and the extraction of the wire from the sample using one of two methods. The first method is the basic mass loading used in phase 2; for study iii, data was also collected from a computer controlled tensile test machine. The objective results are supported by subjective evaluations which focused on the weavability of the samples and their ability to produce cloth of a good quality.

4.2.1 Phase 3, study i: Influence of fabric sett (epi) and integration of Duron yarn on NiTi wire extraction, using the basic mechanical mass loading method

Focus
Woven structures:

- Sett (ends per inch)
- Yarn
- Extracted component

Evaluation:
Bend testing

- Wire extraction tensile test (basic mechanical mass loading)

4.2.1.1 Aims and method

In phase 2, study i, it was noted that the coverage of the NiTi wire was greatly improved as a result of increasing the number of ends per inch. It was, however, also noted in samples 24 and 25 that with this increase in epi, a corresponding destabilisation of the woven structure was evident. In phase 2, study iii, a reduction of force required for extraction was noted in the less formable NiTi samples, whilst it increased in those with finer NiTi components. The initial aim of study i in phase 3 was to evaluate the effect over setting of the fabric and woven structure had in relation to the integrated wire. In phase 2, study iii, the evaluation was made of samples that had a selvedge structure; in study iii, plain weave structures of three different levels of sett will be evaluated. This range starts with a slightly over sett fabric at 72epi, and continues through an intermediary point of 96epi, to 144epi (Table 37). In conjunction with the plain weave samples, 2/2 twill, 6-end satin, and the combined weave structure were also investigated at 144epi.

	Mercerized cotton **2/40cc** - 67/2Nm - 2/15tex			
Weave	100% sett epi	% sett at 72 epi	% sett at 96epi	% sett at 144 epi
Plain weave	66.67	105.88%	141.17%	211.76%
2/2 twill	88.37			161.6%
6-end satin	109.5			133.49%
Plain weave Cotton warp Duron weft	60.28			238.36%

Table 37 Ends per inch calculated using Brierley's *theory of empirical maximum w*eavability for a 2/40cc mercerised cotton yarn.

The second part of this study was an initial investigation of the integration of a Duron yarn into a plain weave and the combined structure at both 72 and 144epi. These were the first samples to use Duron, investigating the potential of a yarn that could be heat set.

Key aims of this study were:

- To identify the effect changes in epi and woven structures have on extraction forces required to remove NiTi components from mercerised cotton samples (samples 115 – 147, 159 168, 181 – 191 and 203 – 213).
- To identify the effect the section and surface finish of NiTi components have on the extraction forces required to remove the wires from mercerised cotton samples (samples 115 – 147, 159 – 168, 181 – 191 and 203 – 213).
- Evaluation of samples integrated with heat set Duron yarn (samples 214 - 246 and 258 – 268).
- To identify the effect of the surface finish of NiTi components on extraction forces required to remove the wires from mercerised cotton samples.

4.2.1.2 Overview of samples

This study was split between samples using a cotton warp and weft, focusing on woven structure samples 115 – 213, and those using Duron in the weft (214 – 268) comparing the differences between heat set composites and plain cotton samples (Table 38). For full details of the composition and production of the samples please refer to appendix C.

Sample	Supporting yarn	epi	Weave	NiTi wire	Sample size
115-125	Mercerised cotton	72	Plain weave	115µm, 152µm, 25x445µm, 50x420µm, 170x900µm NiTi components were used in each batch of samples	30x50mm
126-136		96			
137-147		144			
148-158		72	2/2 twill		
159-169		144			
170-180		72	6-end satin		
181-191		144			
192-202		72	Plain weave and 2/2 twill		
203-213		144			
214-224	Mercerised cotton warp and twill Duron plain weave picks	72			
225-235		144			
236-246	Mercerised cotton warp Duron weft	72	Plain weave		
247-257		96			
258-268		144			

Table 38 Overview of samples produced in phase 3, study i.

4.2.1.3 Results

It could be claimed that there are no unfavourable results when investigating both the positive and negative transfer of control from the wire to the textile, as both extremes are required for the successful development of the secondary level of indirect control. In fact, results that would be viewed as unfavourable are those that show little or no difference in performance between variables. If a limited variation in results was seen, it would reduce the possibilities of being able to affect the behaviour of the wire through changes in the textile structure. For this reason, this investigation focused on understanding the properties, particularly the interfacial relationship between the woven structures, the supporting yarn and the inserted NiTi components, so that future developments can manipulate and combine variables to maximise the effects required.

The effect of changes in epi and woven structure on the extraction forces required to remove NiTi components from mercerised cotton samples (samples 115 – 147, 159 - 168, 181 – 191 and 203 – 213)

The effect the number of ends per inch in a plain weave fabric has on the extraction load of the results showed that an over sett cloth increased the load required to extract an integrated element up to a point, after which there was a marked reduction in load required to initiate first movement and full extraction in the less formable NiTi components (Figure 57). The samples sett at 144epi showed the same weft ribbing described in section 4.1.1.3, although there was not the corresponding reduction of integrity seen in the samples sett at 168epi (see appendix C. for images of the samples).

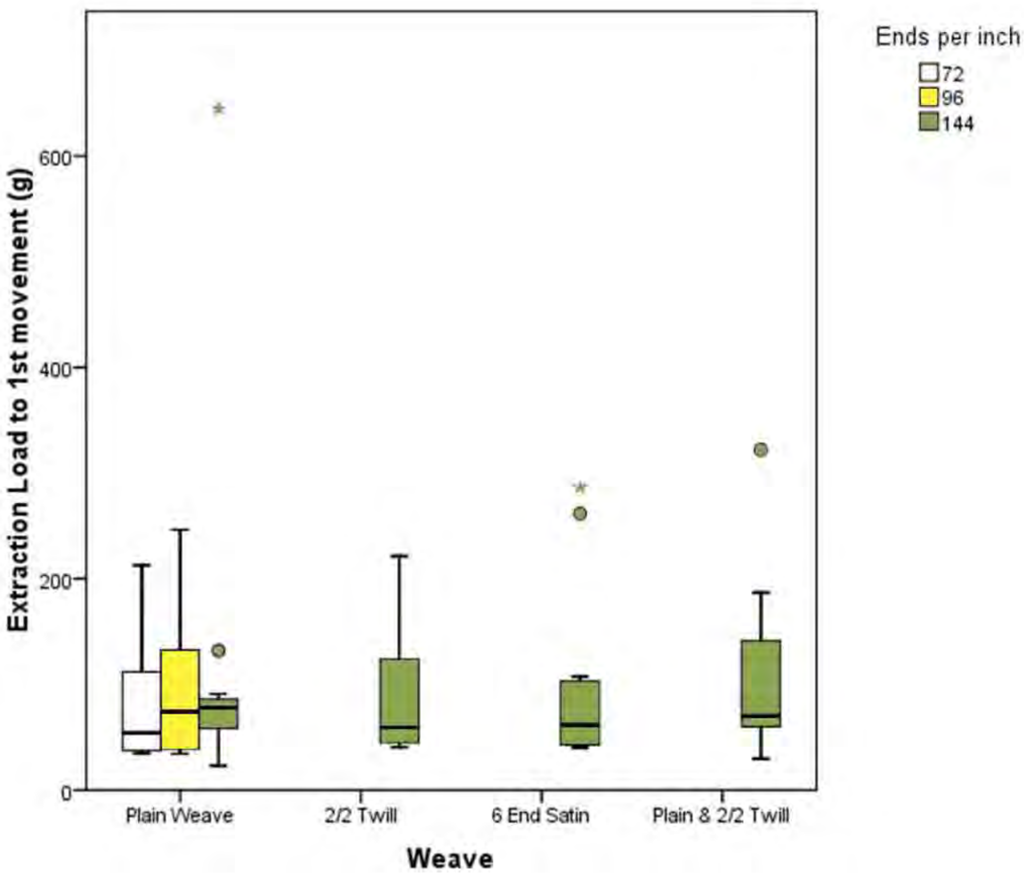


Figure 57 The relationship between epi, woven structure and the load required to induce the 1st movement of an integrated element (results taken from samples 115 – 213) (see Figure 51 for information on the structure of the box plots) (original in colour).

The largest non-outlines and outliers seen in (Figure 57) correspond to the samples that integrate the 25x445µm NiTi ribbon and cotton yarn respectively. These extreme results are caused by the formability of the integrated element to the interlacement of the woven structure and the resulting crimp, which inhibits the removal of the component. The marked difference seen in the 144epi plain weave sample when compared to the 72epi sample is a result of the inserted element conforming to twice te number of interlacements, in contrast to the less formable inserted NiTi components which are more easily extracted from the cloth.

Also shown in Figure 57 are the results from the 2/2 twill, 6-end satin and combined weave sett at 144epi. Given that the four woven structures were over sett to varying degrees, a full analysis of the effect the woven structure had is not possible from these results. It is interesting to note that as was seen in phase 2, study iii although the integrated elements in the combined weave were woven in plain weave, the results are slightly higher than those of the 2/2 twill. This reinforces the indications that the combination of the interlacements in the plain weave and looser structure of the 2/2 twill increase the levels of friction compared to samples of solely plain weave, or 2/2 twill.

The results of the bend testing illustrated in Figure 58 show a clear inverse correlation with those in Figure 57. The results indicate that a stiffer fabric with lower bend angles is more appropriate for restricting the movement of the NiTi components within the woven structure, and increasing the load required for the initiation of 1st movement.

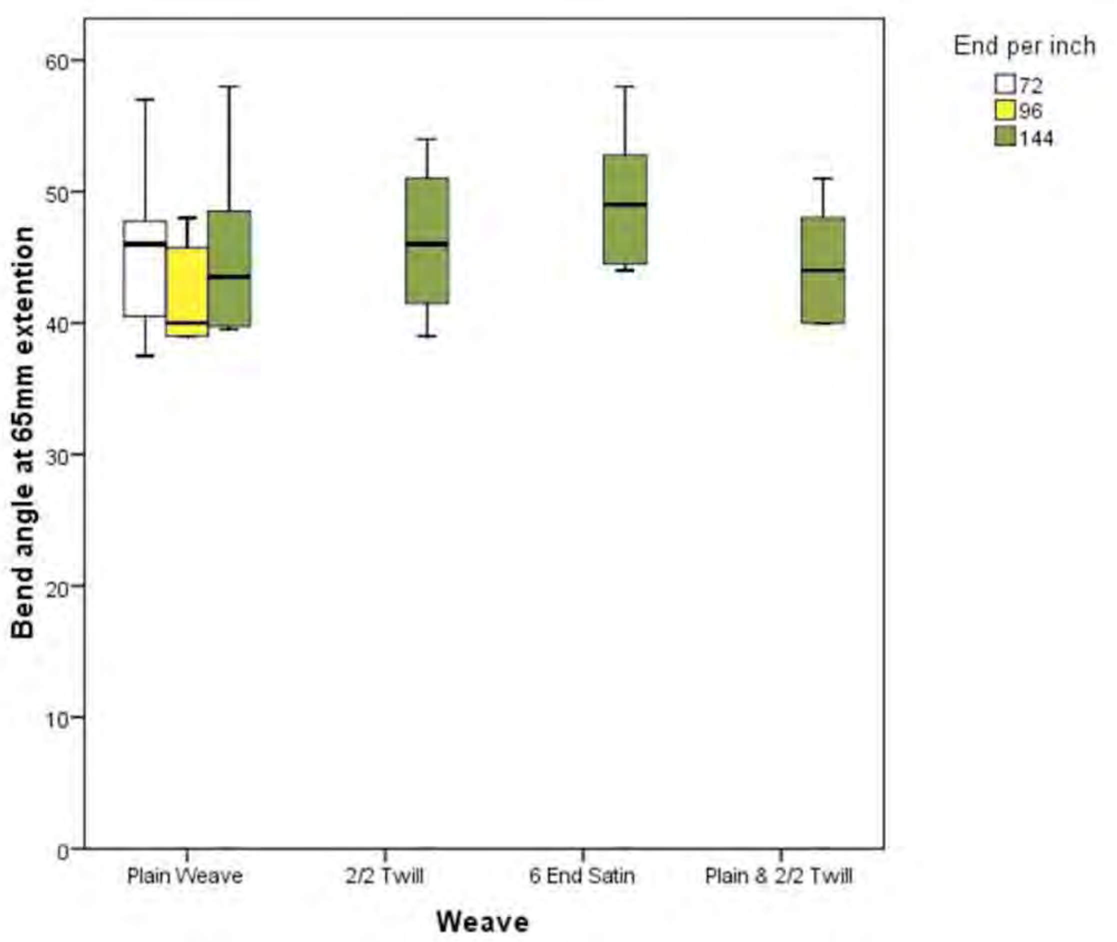


Figure 58 Comparison of bend angles at 65mm extension (results taken from samples 115 – 213) (see Figure 51 for information on the structure of the box plots) (original in colour).

The effect of the section and surface finish of NiTi components on the extraction forces required to remove them from mercerised cotton samples (samples 115 – 147, 159 – 168, 181 – 191 and 203 – 213)

As expected, the higher formability and resultant crimping of the cotton, 115µm wire and 25x445µm ribbon, resulted in higher loads required to initiate the first movement of the inserted component (Figure 59). The exception to this pattern was 170x900µm ribbon, which required a higher than expected load, with even the lowest readings for the 170x900µm ribbon exceeding those for the 50x445µm ribbon. Another noticeable exception for the 170x900µm ribbon was shown with respect to surface finish. The other ribbons and wire all indicated an increase in load required to initiate 1st movement in the samples where the integrated NiTi components had undergone additional heat treatment. However, the 170x900µm ribbon showed results to the contrary, with a noticeable decrease in load required for the NiTi components which had undergone the additional heat treatment.

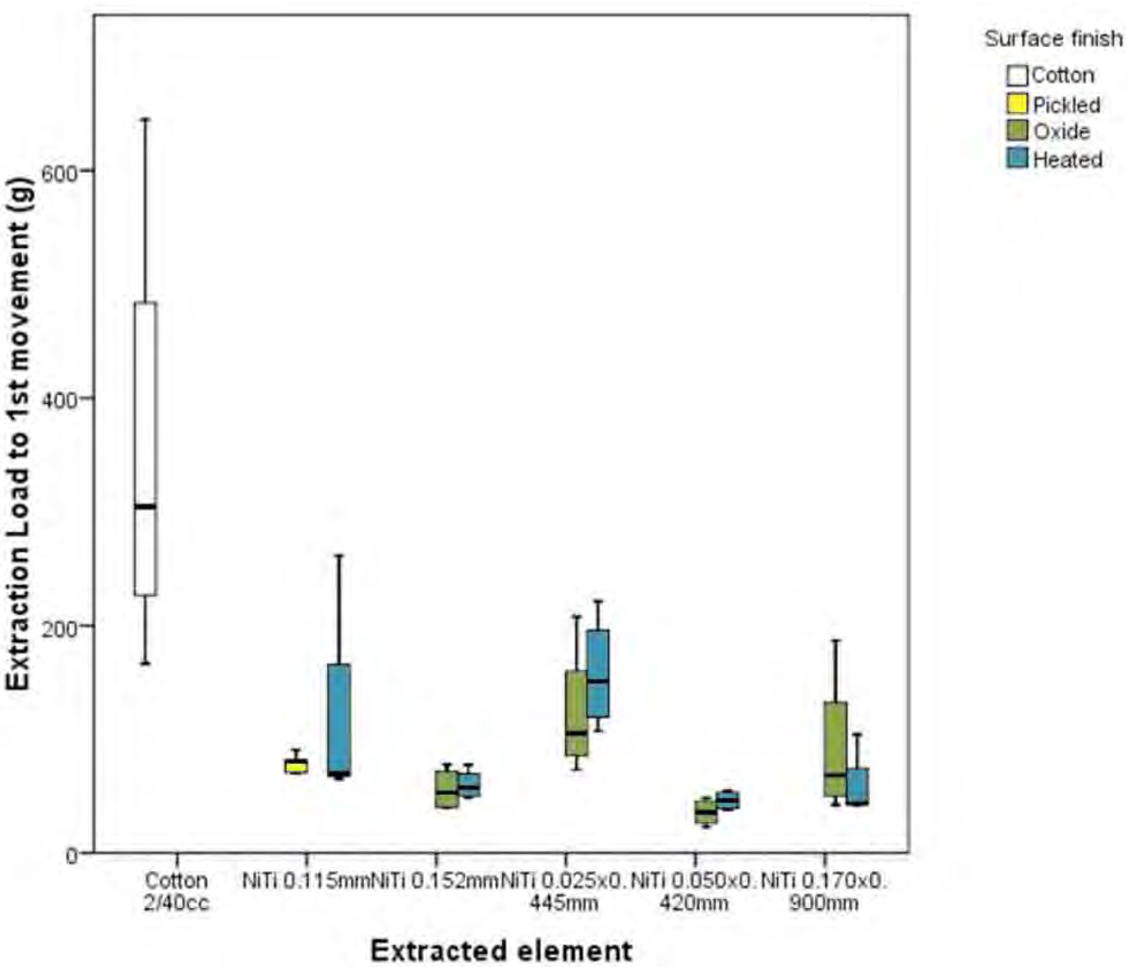


Figure 59 Relationship of a NiTi component, surface finish and load required to initiate 1st movement (results taken from samples 115 – 213. 144 epi samples only) (see Figure 51 for information on the structure of the box plots) (original in colour).

These results indicate that there are either additional factors involved in the relationship between the 170x900µm ribbon and supporting structure or that there were inconsistencies in the testing of these samples. The effect of the surface finish and cross section of the NiTi are investigated further in phase 3, study ii.

Evaluation of samples integrated with heat set Duron yarn (samples 214 - 246 and 258 – 268)

The second part of this study is an initial investigation into the effects that heat set Duron yarn had on the integrated NiTi components when it was inserted parallel to them in the weft. The samples in this part of the study used plain weave, with combined weave structures and sett at both 72 and 144epi. Due to the stiffening of the samples after heat setting, bend testing was not appropriate as, at 65mm extension, there was no notable deflection.

The effect the number of epi had on the two woven structures can be seen in Figure 60. The cotton control threads in samples 214, 225, 236 and 258 snapped during extraction from the heat-set Duron. Due to the snapping of the cotton yarn, true extraction loads were not obtained. To prevent the distortion of the results, the readings for samples 214, 225, 236 and 258 were removed from the analysis. Initial investigation of the results would suggest an increase in load for the 72epi samples across both woven structures. However, on closer reading of the results for the plain weave samples (cotton warp Duron weft), taking into account the lower median of the 72epi samples and the outliers for the 144epi samples, this was not conclusive.

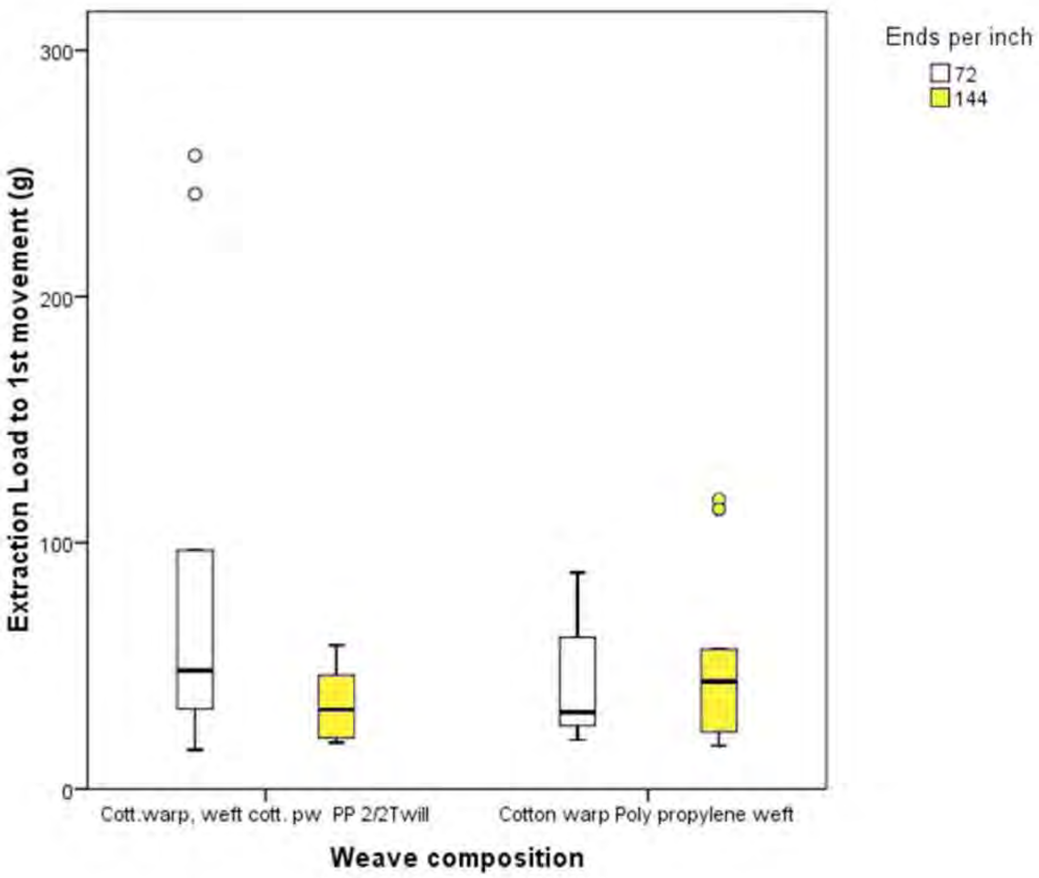


Figure 60 The influence epi has on the two Duron integrated structures (results taken from samples 214 – 268 excluding 214, 225, 236 and 258) (see Figure 51 for information on the structure of the box plots) (original in colour).

The effects of the surface finish of a NiTi component on the extraction forces required to remove them from mercerised cotton samples

In Figure 61 a clear trend can be seen across all the wires and ribbons, in that the samples with integrated wires that had undergone the additional heat treatment required a notably larger load than those in the *as bought* state. Although having a higher outlier, the exception to this was the 115µm wire which had a pickled finish in its *as bought* state. These results suggest that when applied to previously oxidized surfaces, the friction between the wire and supporting structure is increased, whereas the friction was reduced on the pickled surface. The influence of surface finish is explored further in phase 3, study ii.

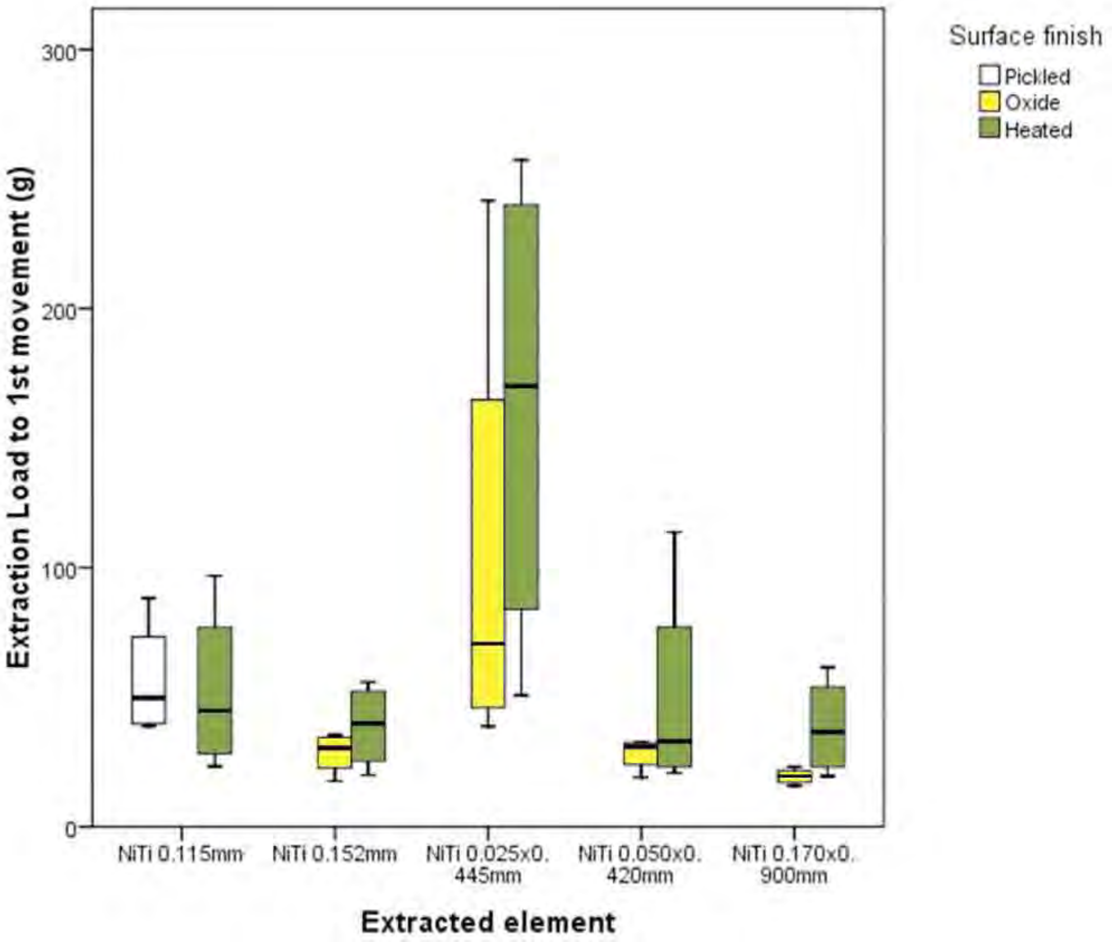


Figure 61 Relationship between the NiTi component, surface finish and load required to initiate first movement. Results taken from samples 214 – 268 (excluding 214, 225, 236 and 258) (see Figure 51 for information on the structure of the box plots) (original in colour).

4.2.1.4 Summary of results for phase 3, study i

This study has successfully demonstrated that by altering specific variables, such as the woven structure and sett of the cloth, both increases and reductions in the force required to initiate the first movement of an inserted NiTi wire can be achieved. The differences in structure can be located along the length of a single wire or ribbon, resulting in changes to the behaviour of and shape transfer from the NiTi component. Key conclusions of this study were:

- As was seen in phase 2, study iii, the use of very fine wires or ribbons, such as the 25x445µm ribbon that can conform to the crimp of the woven structure, can also be used to offer a higher resistance to extraction. The elements that easily conform to the interlacements of the woven structure, show a corresponding rise in load required with the increase in ends per inch. The reverse is seen in the less formable elements that require a tighter packing of the weft threads, which decreases with the increase in epi.
- The correlation of results seen in Figure 59 and Figure 58 shows that an increase in the ability of a woven structure to secure an integrated NiTi component, is in part dependent on the tightness of the structure, and as such, a stiffer cloth with a higher number of interlacements to ends, for example, plain weave, is required.

- The results in this study for both the mercerised cotton and the Duron samples give a strong indication that the additional heat treatment of the wires prior to insertion into the woven structure increases the loads required to initiate their removal from the cloth. This relationship is investigated further in phase 3, study ii, using additional types of supporting yarn.

When comparing the results from the mercerised cotton and Duron samples, there is a marked decrease in the load required to initiate first movement in the latter samples. These results were unexpected; in fact, the reverse had been predicted, as it had been thought the heat setting of the Duron would increase the bond. In the samples the Duron formed a channel which allowed the NiTi component to pull smoothly between the warp threads once the limited interfacial bond had been broken. As part of phase 3, study ii, the use of Duron yarn is further investigated with different combinations of structure, both with and without mercerised cotton yarn.

4.2.2 Phase 3, study ii: Influence of yarn and woven structure on the extraction of NiTi components, using the basic mechanical mass loading method

Focus:

Sample dimensions

Woven structures

Supporting yarn

Extracted component

- Dimensions and cross section
- Surface finish

Evaluation:

- Bend
- Wire extraction tensile test (basic mechanical mass loading)

4.2.2.1 Aims and method

Phase 3, study ii, constitutes the main body of the empirical work, producing and testing a comprehensive number of samples that directly investigate and offer for evaluation combinations of the main variables. The results collated from this study were for static friction, demonstrating the peak force required for the integrated NiTi component to overcome the friction with the supporting structure and initiate first movement. The evaluation of static friction was important in the selection of properties for the direct transfer of shape to the structure and as holding sections in the development of secondary movement. Once the static friction had been overcome and dynamic friction became applicable, the accuracy of the placement of the NiTi component in the structure had been compromised, with inconsistencies in the shape transfer to the supporting structure occurring as a result.

In addition to the 30 x 50mm samples produced in the previous studies, two separate sets of samples were woven in combinations of specific variables. The first set consisted of samples that were 30 x 100mm, providing results for samples of twice the standard length, the second set of were 100 x 100mm and tested under lateral tension. This final evaluation would indicate the effect that tightening the samples' crimp has on the extraction of the wire. To standardise and increase comparability between samples, the sett of each sample type was calculated using Brierley's *theory of empirical maximum weavability*, based on the differences in woven structure and yarn type (Table 39).

	Using Brierley's Theory of Empirical Maximum Weavability															
Warp	Merc cotton				Kevlar				Polyester				Duron			
	2/40cc - 67/2Nm - 2/15tex				2/48cc - **80/2Nm** - 2/12.5tex				1/17cc - **29/1Nm** - 35tex				1/20cc - 34/1Nm - **300dtex**/72fil			
	epi	reed	epd	epi	epi	reed	epd	epi	epi	reed	epd	epi	epi	reed	epd	epi
Plain weave	66.67	20	3, 3, 4.	**66.67**	72.65	24	3	**72**	61.93	20	3	**60**	54.31	18	3	**54**
2/2 Twill	88.37	24	3, 4, 4.	**88**	96.22	24	4	**96**	81.15	20	4	**80**	71.16	24	3	**72**
Plain weave with cotton weft													60.16	20	3	**60**
2/2twill with cotton weft													78.84	18	4, 4, 5	**78**
Plain weave cott/PP warp cotton weft													63.5	18	3,4	**63**
2/2 will cotton /PP warp cott weft													81	18	4,5	**81**

Key	
epi -	Warp ends per inch
Reed -	Dents per inch
epd -	warp ends per dent

Table 39 Calculation for the epi used in phase 3, study ii in relation to the woven structure and yarn type.

Using comparative weave values at around 100% sett would enable a benchmark to be established from which the variances of over and under setting could be investigated more fully in a future study.

Key aims of this study were:

- Evaluation of differences in rigidity of the samples using the bend angle.
- Extraction testing evaluations based on
    - Support yarn, woven structure and extracted component
    - Extracted component
    - Extracted component and woven structure
    - Surface finish of the NiTi component
    - Sample size
    - Lateral tension in the sample

4.2.2.2 Overview of samples

The samples produced in this study cover a wide range of variables and combinations providing a detailed record of the relationship between a variety of inserted NiTi components and supporting structures. Table 40 provides an overview of the variables covered in this study with justification for the specific questions to be answered.

Sample	Supporting yarn	epi	Weave	NiTi	Sample size
269-279	Mercerised cotton	66	Plain weave	*b*	30x50mm
280-285					30x100mm
286-291					100x100mm
292-302		88	2/2 twill		30x50mm
303-308					30x100mm
309-314					100x100mm
315-325			Plain weave & 2/2 twill		30x50mm
326-331					30x100mm
332-337					100x100mm
338-348	Kevlar	72	Plain weave	*b*	30x50mm
349-354					30x100mm
355-360					100x100mm
361-371			2/2 twill		30x50mm
372-382		96			30x50mm
383-388					30x100mm
389-394					100x100mm
395-405			Plain weave & 2/2 twill		30x50mm
406-411					30x100mm
412-417					100x100mm
418-428	Polyester	60	Plain weave	*b*	30x50mm
429-434					30x100mm
435-440					100x100mm
441-451		80	2/2 twill		30x50mm
452-457					30x100mm
458-463					100x100mm
464-474			Plain weave & 2/2 twill		30x50mm
475-480					30x100mm
481-486					100x100mm
487-497	Duron warp Mercerised cotton weft	60	Plain weave	*b*	30x50mm
498-503					30x100mm
504-509					100x100mm
510-520		78	2/2 twill		30x50mm
521-526					30x100mm
527-532					100x100mm
533-543			Plain weave & 2/2 twill		30x50mm
544-549					30x100mm
550-555					100x100mm
556-566	Duron	54	Plain weave	*b*	30x50mm
567-572					30x100mm
573-583		72	2/2 twill		30x50mm
584-589					30x100mm
590-600			Plain weave & 2/2 twill		30x50mm
601-606					30x100mm
607-617	Mercerised cotton & Duron warp. Mercerised cotton weft	72	Plain weave	*b*	30x50mm
618-623					30x100mm
624-634		112	2/2 twill		30x50mm
635-640					30x100mm
641-651			Plain weave & 2/2 twill		30x50mm
652-657					30x100mm

b 115µm, 152µm, 25x445µm, 50x420µm, 170x900µm NiTi components were used (in the case of the Duron samples, a cotton yarn was used).

Table 40 Overview of samples produced in phase 3, study ii.

4.2.2.3 Results

Given the number and range of samples and variables tested, not all permutations are covered in this results section. Instead, all results and detailed records of the composition have been entered into a comprehensive database that acts as a resource for further and deeper investigation into specific variables and combinations. As with phase 3, study i, the results for the samples containing the heat-set Duron yarn have been evaluated in separate charts. As in phase 3, study i, this is to avoid skewing the results because of the different mechanisms used with the heat-set Duron samples, relying on the direct bond with the component rather than the friction and holding potential of the woven structure or yarn. This was also the case for the 170x900µm ribbon which dominated the woven structure due to its *as rolled*, work hardened condition.

Figure 62 was created to provide an overview of all the samples tested in this study, identifying and ordering the variables investigated. Providing an overview in this way highlights trends that become clearer with closer investigation, as well as those that could later skew the results; for instance the exceptionally high loads required to remove the additional Kevlar components in the 30x100mm plain weave sample and the 100x100mm sample. The most pronounced results in Figure 62 are those which mark of the sharp divide between the high readings of the sample containing heat-set Duron and the much lower readings for the cotton, Kevlar and polyester. This outcome is of particular interest after the unexpected results in phase 3, study i, which showed that when the Duron yarn is inserted parallel to the component to be extracted, the load required to achieve the first movement was less than for the Duron free sample. This difference was a result of the surface contact between the Duron and the NiTi component, visible in two ways. Firstly, the results for the 170 x 900µm ribbon in the Duron free samples are amongst the lowest when compared to the other inserted NiTi components. By contrast, in the 100% Duron warp samples, the increased surface contact of the 170 x 900µm ribbon, achieved some of the highest loads in the study. Secondly, across all the NiTi components, there is a lowering of results in the 50% - 50% Duron - mercerised cotton mix when compared to the 100% Duron warps.

		30x50mm			30x50m (additional heat teatment)			30x100mm			100x100mm (under tension)		
		Plain weave	Plain & 2/2 Twill	2/2 Twill	Plain weave	Plain & 2/2 Twill	2/2 Twill	Plain weave	Plain & 2/2 Twill	2/2 Twill	Plain weave	Plain & 2/2 Twill	2/2 Twill
Cotton	Cotton 2/40cc	135	117	205				239	442	80	702	766	622
	NiTi 115µm	85	54	56	47	63	53	166	145	121	1171	338	434
	NiTi 152µm	50	61	43	52	44	30	97	120	66	499	471	539
	NiTi 25x445µm	148	95	85	142	81	132	222	137	156	346	535	396
	NiTi 50x420µm	28	39	39	34	32	21	97	56	35	639	360	456
	NiTi 170x900µm	40	71	27	45	65	93	80	111	51	668	356	640
Kevlar R	Kevlar 80/2Nm	330	555	885				2097	369	605	2177	2834	1919
	NiTi 115µm	200	189	146	276	184	138	425	373	304	610	576	462
	NiTi 152µm	207	131	69	209	129	80	303	189	179	872	799	458
	NiTi 25x445µm	29	171	222	242	224	204	437	280	370	637	650	644
	NiTi 50x420µm	87	125	57	133	169	88	184	162	199	681	899	
	NiTi 170x900µm	123	91	47	88	104	70	258	159	197	1072	1132	865
Polyester	Polyester 35 tex	502	297	385				481	432	420	1087	679	659
	NiTi 115µm	241	232	202	235	228	170	311	348	357	598	995	
	NiTi 152µm	189	223	175	208	338	181	529	247	327	1054	568	564
	NiTi 25x445µm	259	288	352	32	279	292	331	34	240	771	452	560
	NiTi 50x420µm	275	234	137	288	177	190	475	380	313	699	1059	494
	NiTi 170x900µm	217	187	234	180	224	157	385	361	349	1316	1072	944
Duron	Cotton 2/40cc	672	740	753				761	759	742			
	NiTi 115µm	1062	473	705	824	569	732	743	508	842			
	NiTi 152µm	861	435	590	594	625	794	556	558	519			
	NiTi 25x445µm	797	676	967	965	1393	967	826	593	1435			
	NiTi 50x420µm	1125	105	214	830	942	917	1018	856	1035			
	NiTi 170x900µm	1949	2513	2736	1401	2584	1917	2528	3727	3991			
Duron CL warp Cotton weft	Cotton 2/40cc		661	782				713	665	624	2003	694	737
	NiTi 115µm		518	647		517	520	503	583	572	1172	844	
	NiTi 152µm		529			614	275	712	652	546	877	954	1025
	NiTi 25x445µm		392	528		545	1256	350	269	1672	1624	856	1050
	NiTi 50x420µm		232	987		1216	563	573	199	1190	1866	1672	1766
	NiTi 170x900µm		3000	2561		2420		5353	5027	3613		1646	
Duron CL and coton warp Cotton weft	Cotton 2/40cc	873	735	885					462	665			
	NiTi 115µm	483	537	514	527	487	627	680	533	861			
	NiTi 152µm	64	366	264	96	275	291	223	454	406			
	NiTi 25x445µm	287	423	432	1121	397	503	443	397	408			
	NiTi 50x420µm	415	590	719	590	484	405	1035	1174	997			
	NiTi 170x900µm	283	642	956	676	678	727	598	1188	1175			

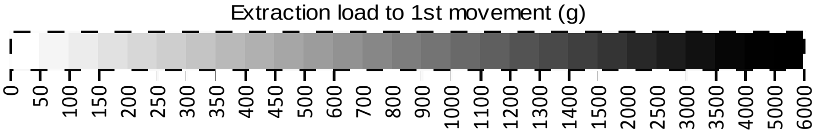


Figure 62 All results for extraction loads to first movement.

Bend angle testing

Evaluation of differences in the rigidity of samples using the bend angle

Initial analysis of the samples prior to testing determined that due to the rigidity and pre-formed arc of the 170x900µm ribbon, bend testing would not be possible. For a similar reason, after heat setting, the samples woven with a Duron warp and weft were also unsuitable for bend testing due to their stiffness, and readings of zero were duly recorded. The exceptions to the non-testing of the Duron samples were those containing both cotton and Duron in the warp for which readings were taken.

The results from the bend angle testing of the free NiTi components (Figure 63 a) show relatively similar results for the 115µm, 152µm wire and 50µmx420µm ribbon, where as the 25µmx445µm ribbon has a much greater bend angle. The extreme result for the 25µmx445µm ribbon compared to the other NiTi components tested is not duplicated in the results for the woven samples (Figure 63 b) and would indicate that in the samples presented here the NiTi components do not have a noticeable influence on the results.

Bend angle of free NiTi components	
NiTi 115µm	15
NiTi 152µm	18
NiTi 25x445µm	58
NiTi 50x420µm	14
NiTi 170x900µm	

a.

		Bend angle 100mm x 30mm	100mm	30mm	100mm	30mm	100mm
		Plain weave		Plain & 2/2 Twill		2/2 Twill	
Cotton	Cotton 2/40cc	59	56	53	55	45	51
	NiTi 115µm	49	48	43		48	49
	NiTi 152µm	44	50	52	51	52	48
	NiTi 25x445µm	53	66	49	52	53	51
	NiTi 50x420µm	50	47	51	52	51	49
	NiTi 170x900µm						
Cotton and Duron warp, cotton weft	Polyester 35 tex	47		20		38	
	NiTi 115µm	37		35		33	
	NiTi 152µm	36		36		34	
	NiTi 25x445µm	54		44		37	
	NiTi 50x420µm	40		40		35	
	NiTi 170x900µm						
Polyester	Polyester 35 tex	26		24	16	23	25
	NiTi 115µm	24		26	19	26	18
	NiTi 152µm	29		16	18	28	16
	NiTi 25x445µm	31		28	11	31	14
	NiTi 50x420µm	33		32	13	31	23
	NiTi 170x900µm						
Kevlar R	Kevlar 80/2Nm	9	14	10	16	12	14
	NiTi 115µm	10	16	14	14	12	20
	NiTi 152µm	13.5	20	11	11	12	16
	NiTi 25x445µm	12	17	13	20	7	10
	NiTi 50x420µm	18	16	14	10	18	22
	NiTi 170x900µm						

b.

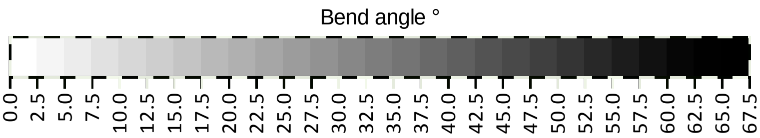


Figure 63 Results from bend angle tests.

a. Shows results from NiTi components free from a woven structure
b. Shows results from a range of woven samples

When evaluating the results for plain weave and 2/2 twill (Figure 64), the plain weave sample showed a greater flexibility with a higher bend angle across all yarn and NiTi variables. In the cotton samples this difference was relatively small but a greater divergence could be seen in the mixed cotton Duron samples. A notable exception to this pattern in the cotton supporting structure was the result for samples using the additional cotton warp yarn.

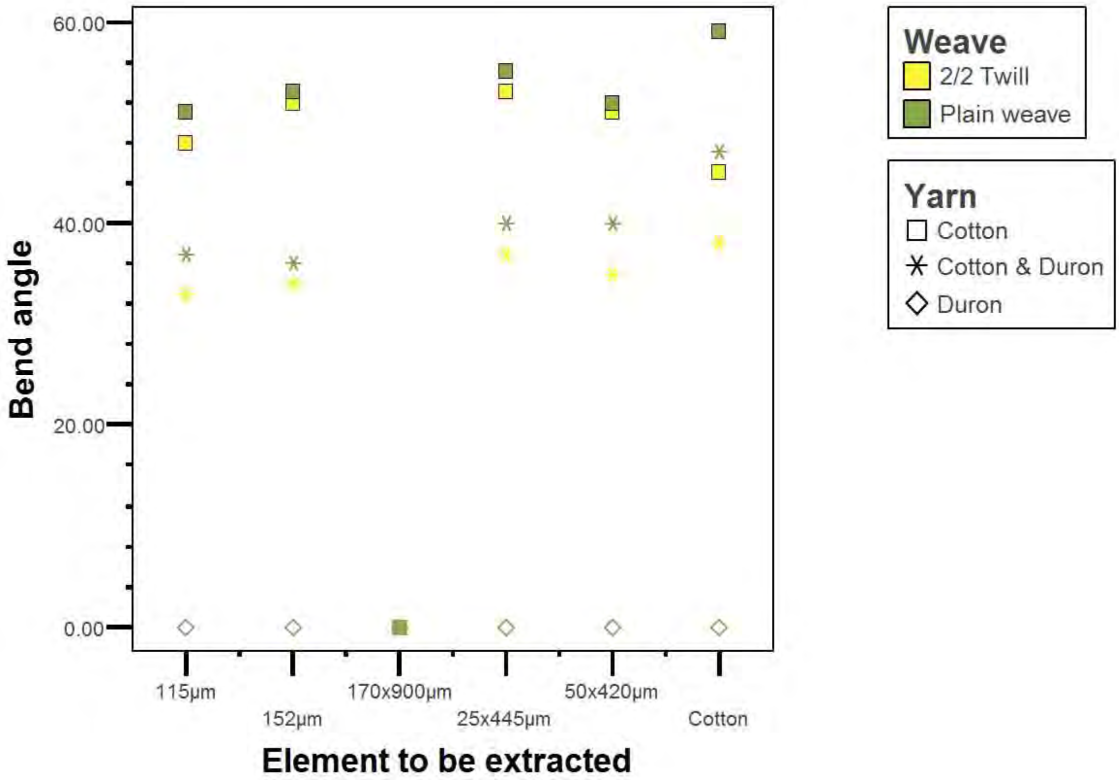


Figure 64 Effect NiTi wire, yarn and weave have on the bend angle at 65mm extension (original in colour).

The results in Figure 65 show a clear correlation between the bend angle and the supporting yarn used, with the cotton sample showing the largest deflection and the Kevlar samples showing the least. As expected, given the increased rigidity of the samples using Duron in both the warp and weft, the sample which consisted of a combined cotton and Duron warp demonstrated less flexibility when compared to the cotton samples, although, overall they recorded the second highest bend angle. This demonstrates the potential for combining the holding properties of Duron without a dramatic loss in flexibility and subsequently the handle of the fabric.

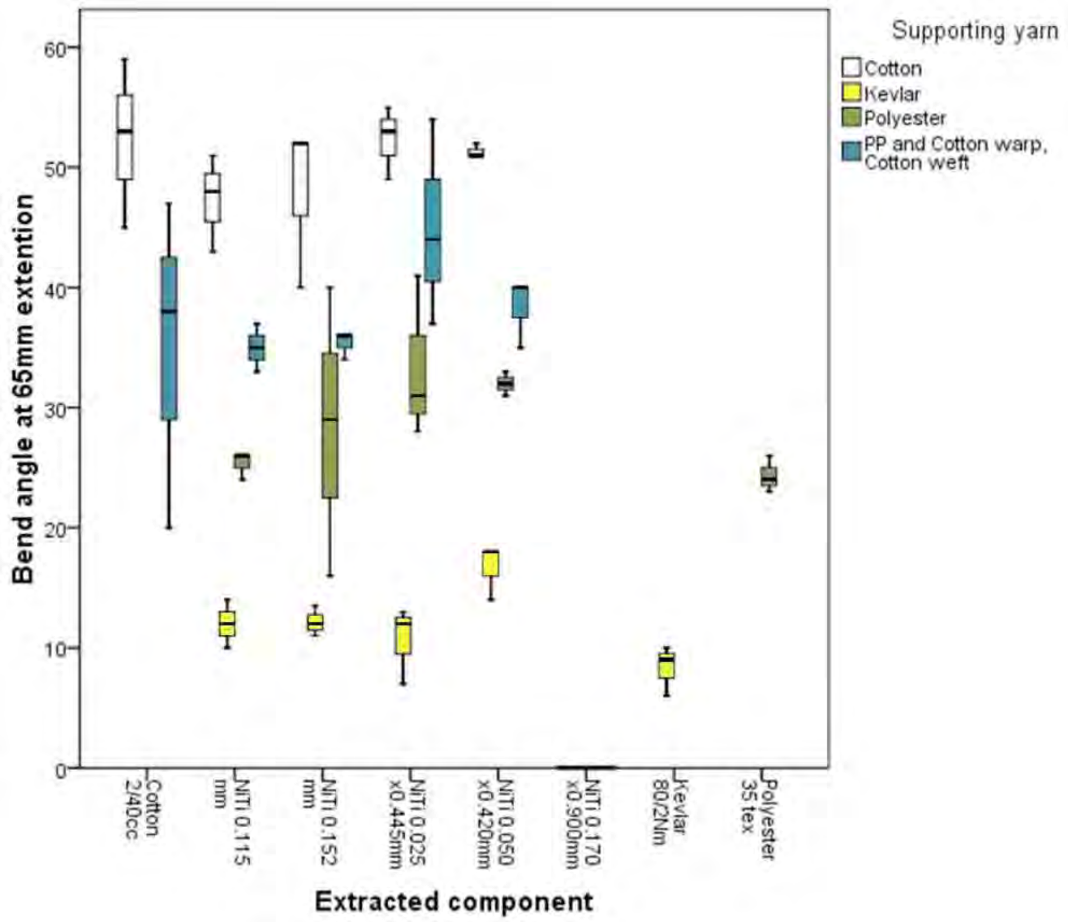


Figure 65 Evaluation of bend angle results by extracted component and supporting yarn from samples 269 – 360, 372 – 555 and 607 – 657 (see Figure 51 for information on the structure of the box plots) (original in colour).

Extraction testing

The results from the extraction testing are recorded here in five sections based on the specific variables being evaluated.

Evaluations based on support yarn, woven structure and extracted component

The results showing the effect the supporting yarn has on the force required to extract the NiTi component from the woven structure are shown in Figure 66. A clear hierarchy can be seen across the samples that do not contain the heat-set Duron, with cotton requiring the lowest forces, followed by Kevlar, and polyester samples. These results are demonstrated across all the extracted components.

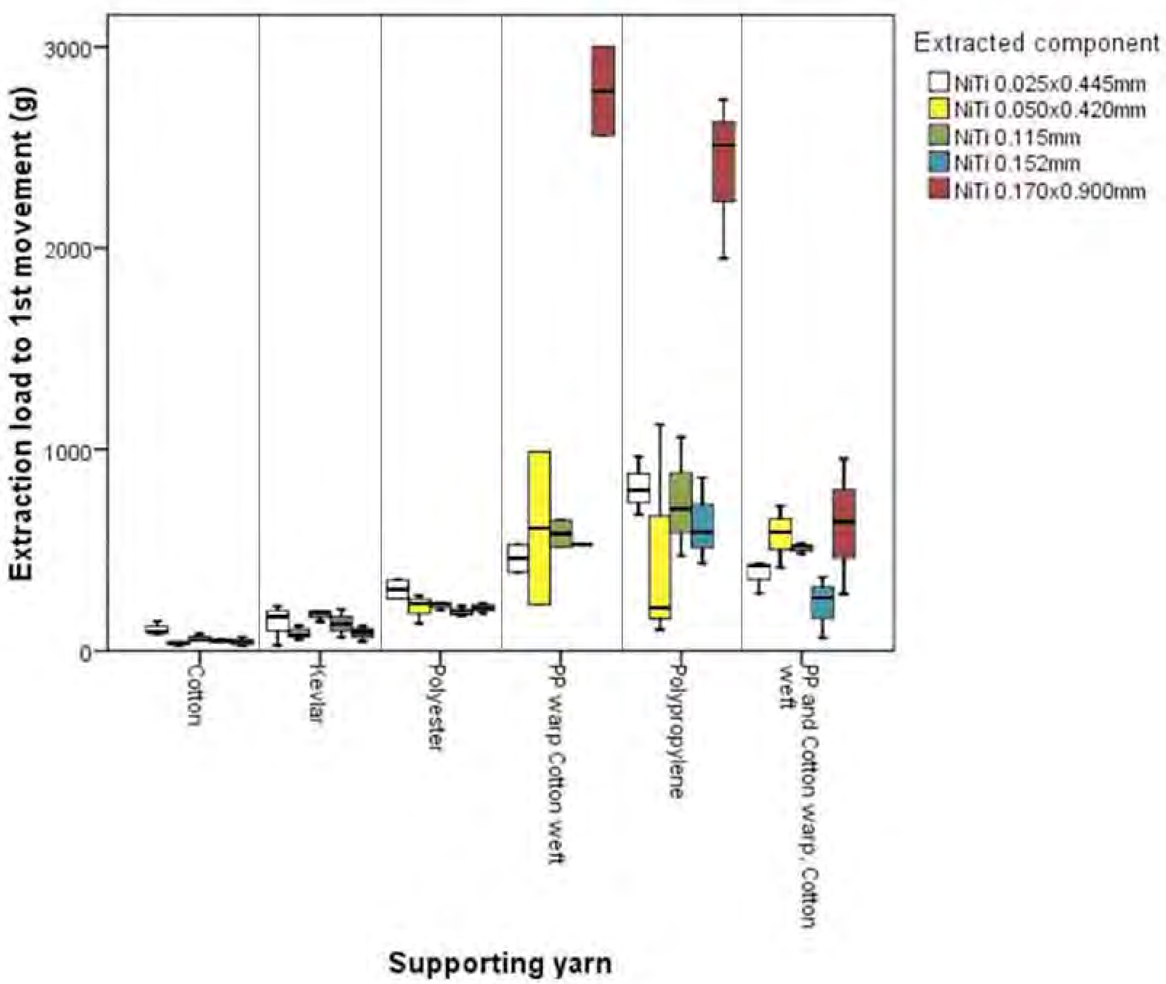


Figure 66 Evaluation of bend angle results by extracted component and supporting yarn from samples 269 – 360, 372 – 555 and 607 - 657

The results for the Duron samples are less clear. Although the general trend shows the 100% Duron sample requiring the highest force, followed by the Duron warp cotton weft, exceptions to this can be seen in the results for both the 50 x 420µm and 170 x 900µm samples, where the 100% Duron sample showed lower results. The mixed samples of Duron and cotton warp, with cotton weft, recorded lower results than the other Duron samples. However, at a mix of 75% cotton to 25% Duron, these samples required substantially higher loads when compared to both the 100% cotton and Kevlar and polyester samples.

The overall results for the Duron samples in this study are of particular interest given the relatively low forces required to extract the NiTi components in phase 3, study i. In the earlier sample, the Duron yarn only ran parallel to the integrated NiTi component and, as discussed in section 4.2.1.3, formed a pocket which, after initial release, required limited force to remove the NiTi. In contrast, both of the sample types incorporating cotton yarn had Duron in the warp. This meant that Duron yarn was placed either side and along the length of the NiTi components, as discussed in section 3.2.4.5. This increase and more complete encapsulation of the NiTi resulted in much higher extraction forces being required to break the initial bond. This was most noticeable in the ribbon samples that had a larger area of surface contact.

Evaluations based on the extracted components

The overview of the results based on the extracted component for the cotton, Kevlar and polyester samples (Figure 67) shows increasing loads required for the finer extracted components. The exception to this is the 50x420µm ribbon, which although the second finest, required the lowest load to initiate the first movement. The surface finish should be ruled out as a contributing factor to this exception, as it was the same in all the samples produced, other than for the 115µm wire where further investigation would be required to ascertain the cause. In contrast, the results in the overview of the heat set Duron samples (Figure 68) demonstrate a clear trend towards the opposite, with the components with the larger surface area, such as the 170x900µm ribbon, needing by far the highest loads to initiate the first movement. Once again, there is an exception to this trend, with the 152µm wire requiring the lowest load rather than the 115µm wire. In this instance, the surface finish of the components may be a factor because, although not directly comparable given the different diameters, the results shown in Figure 68 generally illustrate the need for higher loads to be exerted on the pickled 115µm wire.

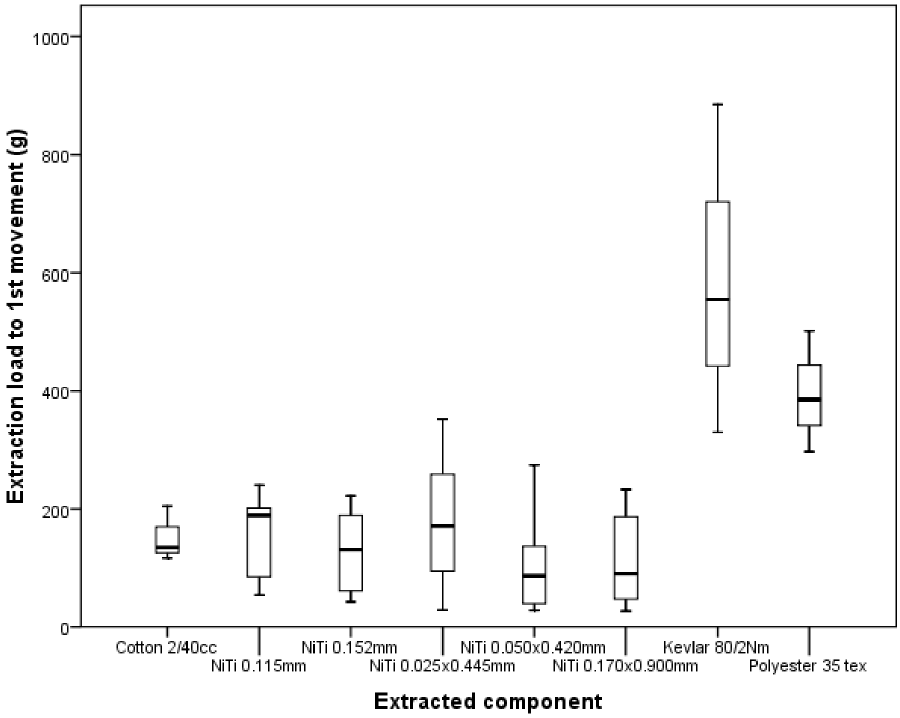


Figure 67 Evaluation of load required to initiate first movement based on the extracted component. Results taken from samples 269 - 657 not including samples 361 - 371 (see Figure 51 for information on the structure of the box plots).

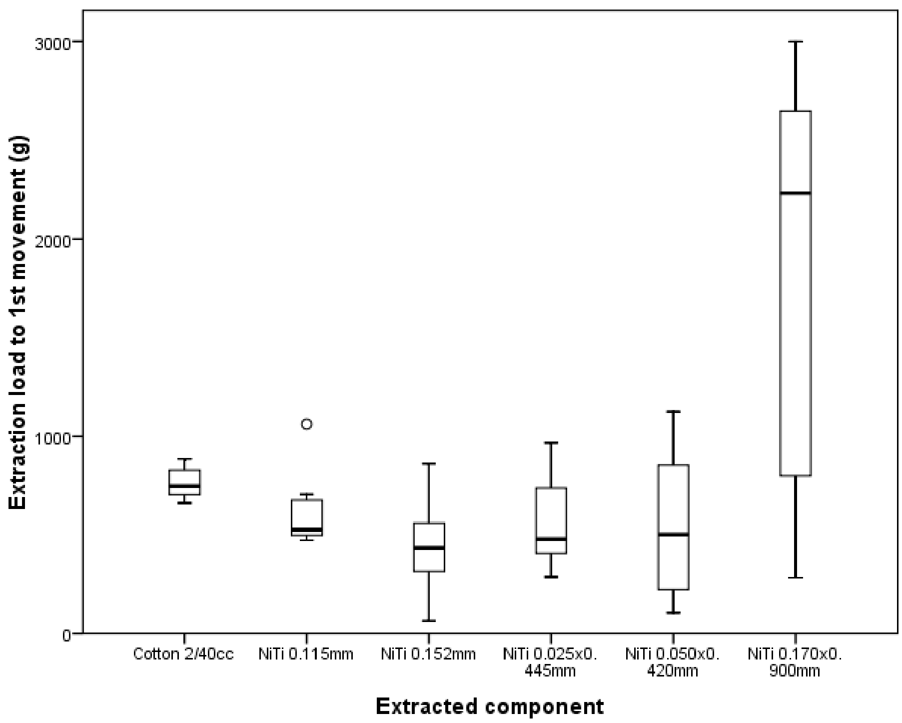


Figure 68 Evaluation of load required to initiate first movement based on the extracted component. Results taken from polypropylene samples 487 - 657 (see Figure 51 for information on the structure of the box plots).

Extracted component and woven structure

When looking closer at the results, focusing on the extracted component in relation to woven structure, both Figure 69 and Figure 70 show that the plain weave structure required the application of the highest loads, with the exception of the 25x445µm ribbon in the samples without the Duron yarn, and the 170x90µm ribbon in the Duron samples. The results for the 2/2 twill and combined weave structures differed between the two sets of samples. In the cotton, Kevlar and polyester samples, with the exception of the 25x445µm ribbon, the 2/2 twill samples recorded the lowest results. This differed from the Duron samples with all but the 170x900µm ribbon showing the combined weave as requiring the lowest loads to initiate first movement. It is of interest to note that the samples that demonstrated the exceptions in these results, recorded a complete reversal in the trend set by the other samples in their section.

These results demonstrate the two different mechanisms at work. Where Duron is not present, it is the tightness of the cloth that prevents the movement of the extracted component, whereas in the Duron samples there is an additional bonding mechanism which consistently places the 2/2 twill above the combined weave, despite them both having the same number of ends per inch. Although, as discussed for Figure 70, the 170x900µm ribbon required the greatest forces, a close look at the results showed a reversal of the trend in other sample sets, with the plain weave sample requiring the lowest load of the three structures. In the heat set Duron samples the results for the cotton yarn relate to breaking strains rather than extraction forces. It should be noted that the results for cotton, Kevlar and polyester in Figure 69Figure 69 are recorded as single bars as they relate to the single control sample tested for each yarn type and woven structure.

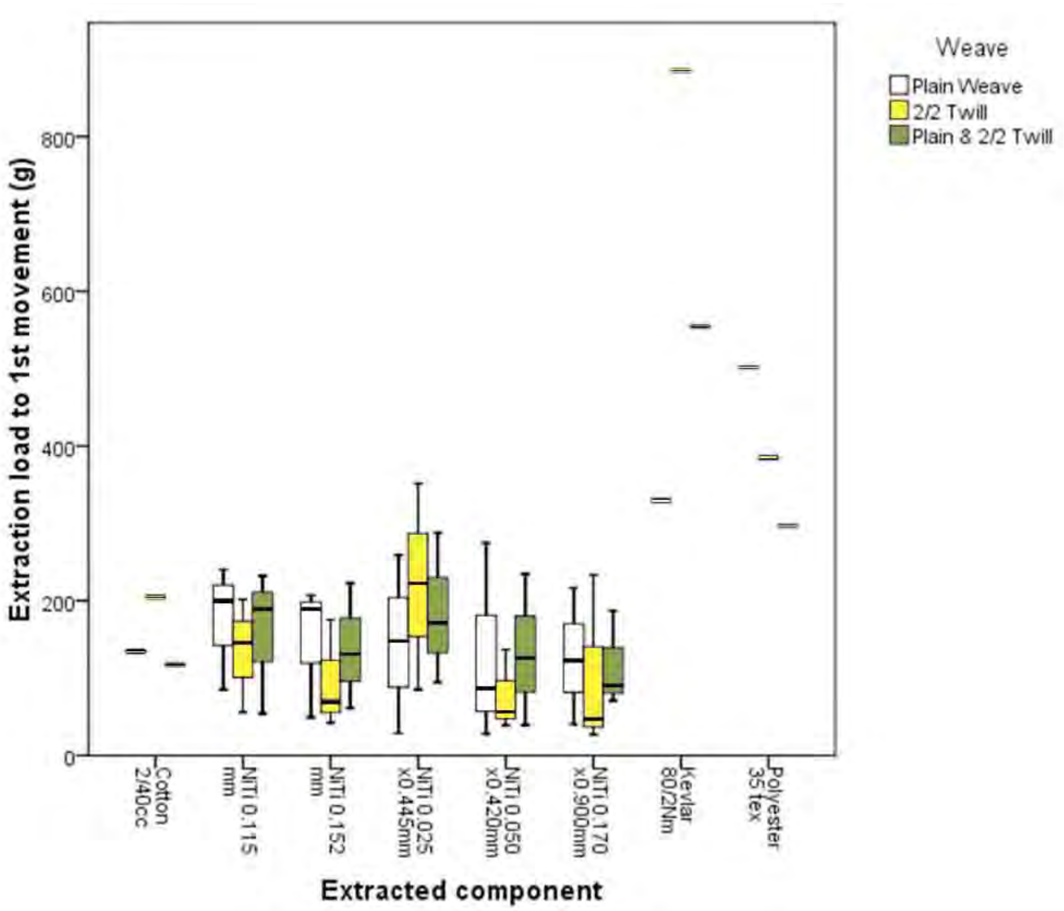


Figure 69 Evaluation of load required to initiate first movement based on the extracted component and woven structure (results taken from samples 269 - 486 not including polypropylene samples, and 361 - 371). (See Figure 51 for information on the structure of the box plots) (Original in colour).

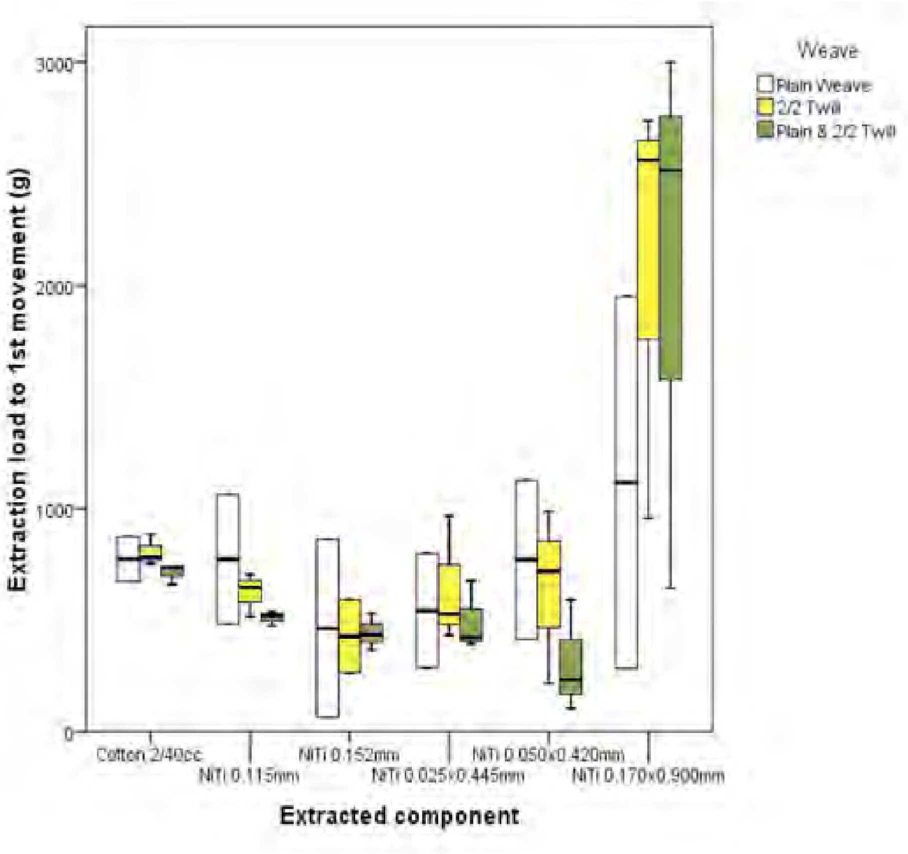


Figure 70 Evaluation of load required to initiate first movement based on the extracted component and weave structure (results taken from polypropylene samples 487 - 657). (See Figure 51 for information on the structure of the box plots) (Original in colour).

Evaluations based on sample size and lateral tension in the sample

This part of the evaluation looked at two separate factors. Firstly the effect that doubling the length of the sample has on the load required to initiate first movement, concentrating on 30x50mm and 30x100mm samples. Secondly investigating the effect the application of tension to the sample perpendicular to the line of extraction had, using the results for the 30x100mm and 100x100mm samples.

Sample size

Isolating the three key variables, the effect the size of sample and subsequent length of integrated NiTi had on the extraction force required to initiate first movement are presented in Figure 71 and Figure 74. To prevent a distortion of the results and to be able to evaluate the differences between the retention of the NiTi component, the evaluation of the extracted components was split, separating the non-heat-set structures, namely cotton, Kevlar and polyester, from the heat set structures containing Duron. Separating these results enabled an evaluation to be carried out on the differences in the increase in interfacial friction between the supporting yarn and the NiTi component, and the bonding between the NiTi and the heat-set Duron. As would be expected, across all the variables the overall results consistently demonstrated an increase in force from the 30 x 100 mm samples when compared to the 30 x 50mm samples. Consistent with the other results recorded in this study, Figure 71 shows that the plain weave samples required the greatest force and the 2/2 twill the least. While this pattern continued in the 30 x 100mm samples, there was a noticeably larger increase in force required by the plain weave samples.

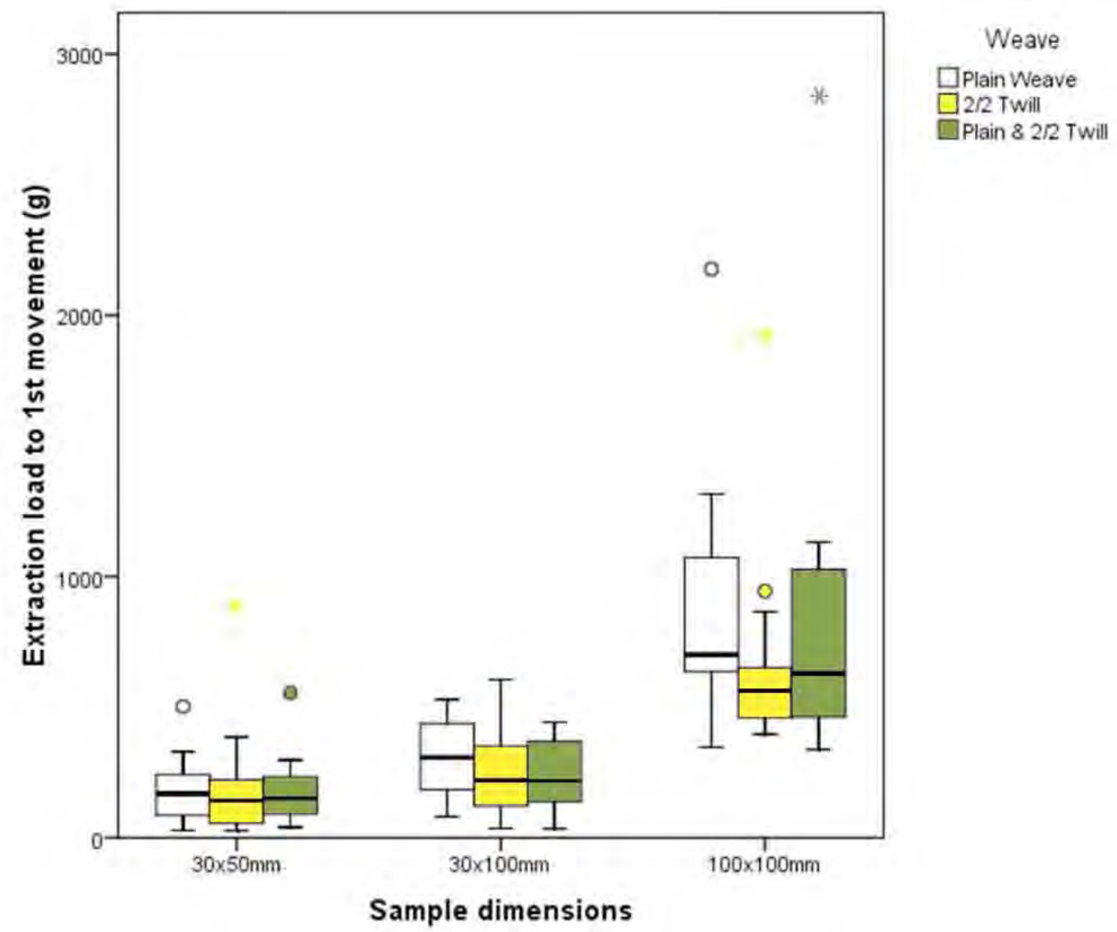


Figure 71 Evaluation of load required to initiate first movement based on sample size and woven structure. (Results taken from samples 269 - 486 not including polypropylene samples, and 361 - 371). (See Figure 51 for information on the structure of the box plots) (Original in colour).

Comparing the results based on the supporting yarn (Figure 72), there is again consistency across the sample sizes from the non-Duron samples, with the cotton requiring the least, force followed by Kevlar, and finally, the polyester samples. Although all the Duron samples required considerably more force in both sample sizes, the increases were less pronounced. Additional points of interest from the results based on the woven structure were the extent of the outliers for the Duron samples, which showed a very wide range of results, as well as the results for the 100% Duron samples, which demonstrated only a limited increase based on sample size.

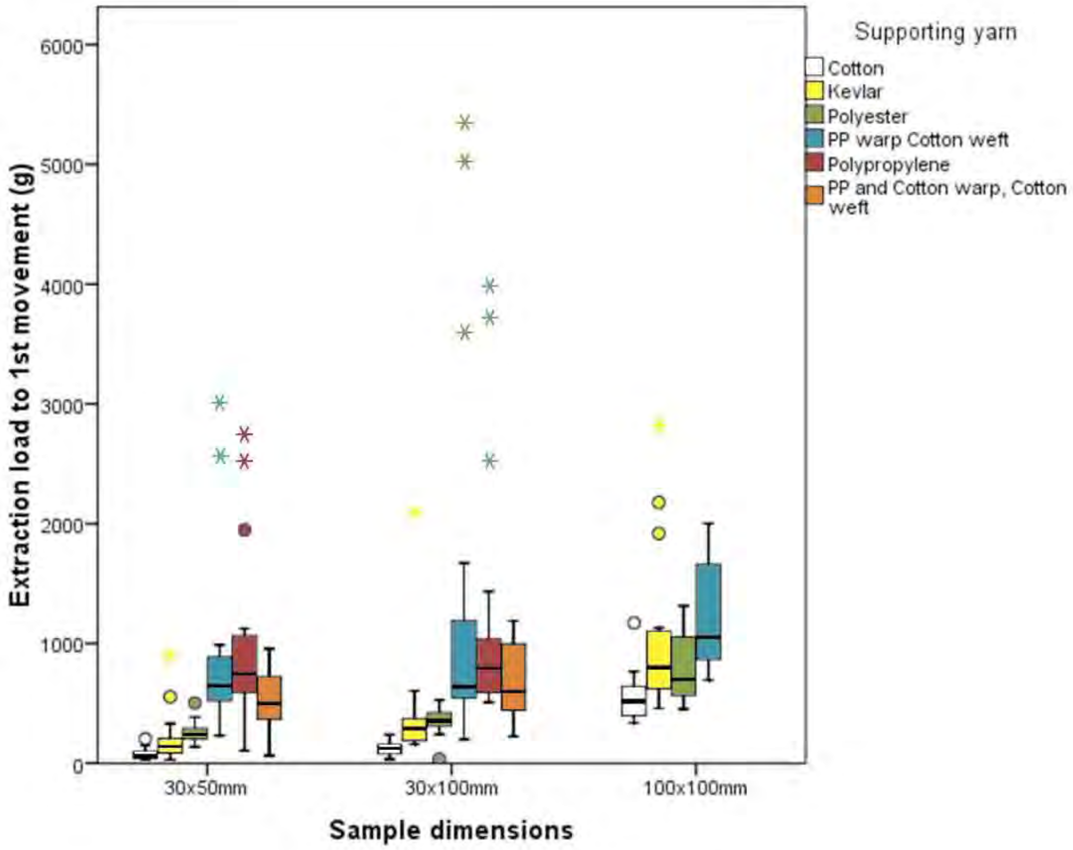


Figure 72 Evaluation of load required to initiate first movement based on sample size and supporting yarn. (See Figure 51 for information on the structure of the box plots) (Original in colour).

The final set of results showed the effects the sample size had on the extracted components, as shown in Figure 73 and Figure 74. A consistent hierarchy existed between the extracted components for forces required to initiate first movement, including a noticeable increase in both the force required and variance of the results for the Kevlar samples. The exception to this increase between sample sizes was from the polyester samples, which only required a small, additional force to demonstrate a consolidation of the overall results (Figure 73).

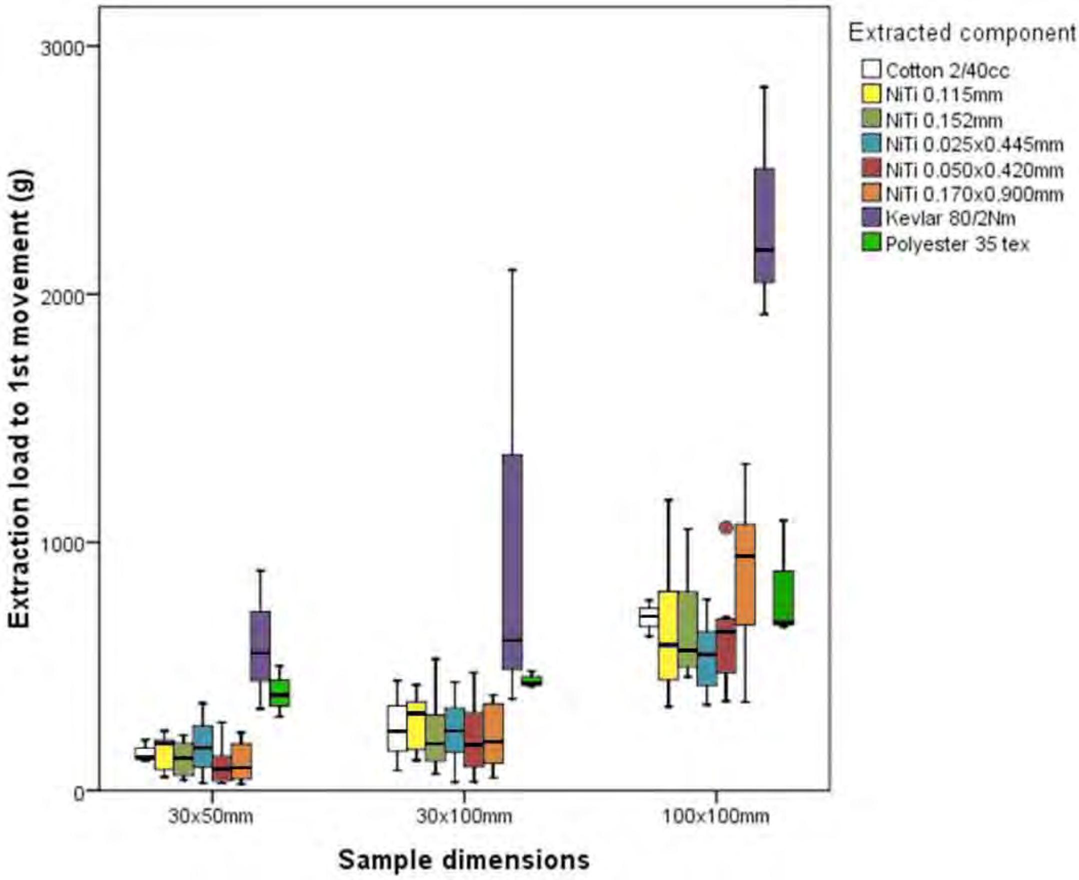


Figure 73 Evaluation of load required to initiate first movement based on sample size and integrated NiTi component. (Results taken from samples 269 - 486 not including polypropylene samples, and 361 - 371). (See Figure 51 for information on the structure of the box plots) (Original in colour).

The Duron results in Figure 74, show a clear pattern between all the extracted components and the sample sizes, as well as an increase in force required to initiate first movement from the 30x100mm samples. The pattern from the extracted components corresponded with the previous results with the exception of the 50x420µm and 170x900µm ribbons. As discussed earlier, because of the increased surface area of the ribbon the bond with the heat set Duron is greater, which instead of showing reduced extraction forces, seen in Figure 73, demonstrated a marked increase in both sample sizes.

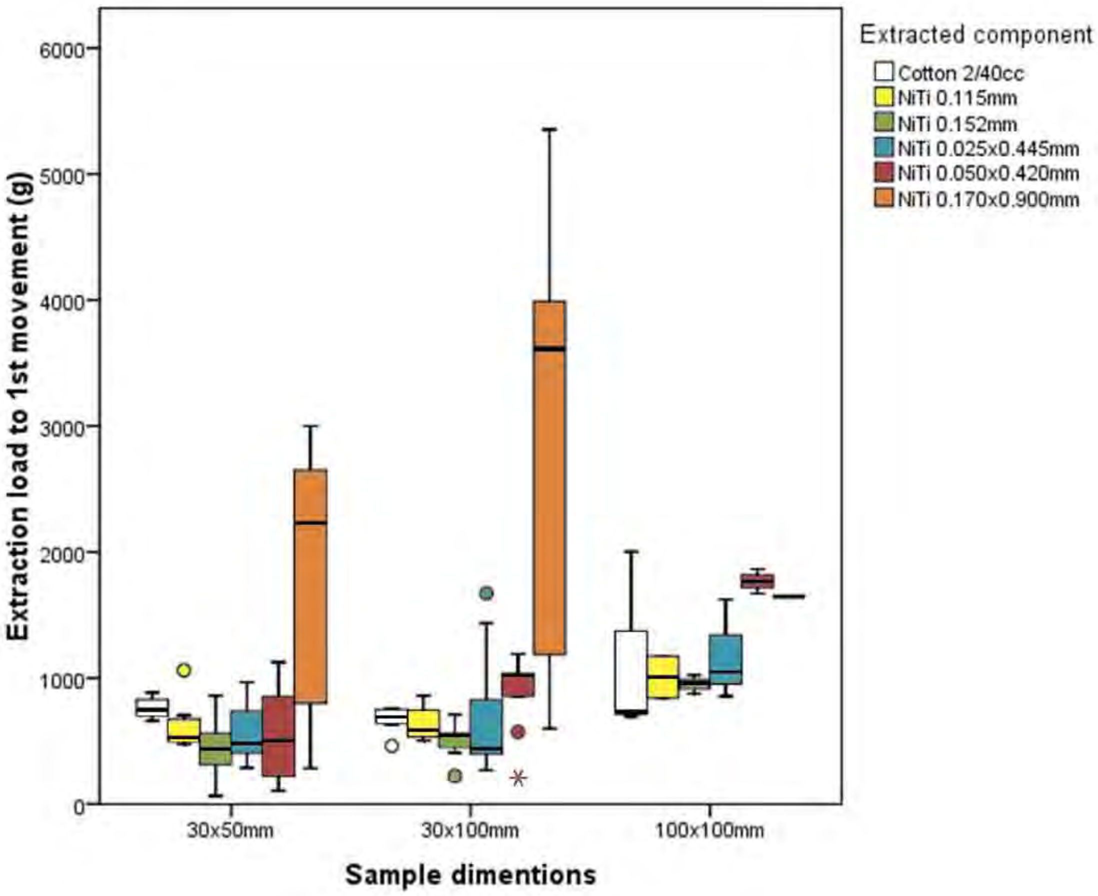


Figure 74 Evaluation of load required to initiate first movement based on sample size and integrated NiTi component. (Results taken from polypropylene samples 487 - 657). (See Figure 51 for information on the structure of the box plots) (Original in colour).

Evaluations based on lateral tension in the sample

The evaluation of the effect of the integrated NiTi component element on extraction forces whilst under tension is again separated between non-heat-set and heat set samples (Figure 71 to Figure 74). Direct comparisons can be drawn between the results for the 30x100mm and the 100x100mm samples under lateral tension, with all the samples requiring a greater force to achieve the first movement in the latter. The effects of the supporting yarn on the initiation of first movement can be seen in Figure 71 and clearly demonstrate the substantial increase in force required in the non-heat-set samples, cotton, Kevlar and polyester. This increase was particularly noticeable in the Kevlar and polyester samples, which under tension require forces equal to the heat set Duron samples.

In Figure 72 the heat-set samples with cotton and Duron warp, and with cotton weft, showed the need for a noticeable increase in force while under tension when compared to the 100% Duron warp. The level of increased force required in these samples suggested that, although set in a polymer matrix, there was enough movement present in the structure to allow the cotton warp threads to exert additional force on the NiTi components.

The results for the non-heat-set samples show the 25x445µm and 50x420µm ribbons demonstrating a marked increase in force required, although notably less than the other NiTi components (Figure 73). This is revealing because in other tests the 25x445µm ribbon has generally required the greatest forces to achieve extraction. Following analysis of the results it can be seen that whilst relaxed, the 25x445µm ribbon conformed to the structure more readily than the other NiTi components. However, under tension, with the straightening out of the warp ends this was reduced and the 25x445µm ribbon conformed to the structure in much the same way as the other NiTi components. This trend was not repeated in the heat set Duron samples (Figure 74) where although more force is required across all the samples, the increased surface area and profile of the ribbons generates a much stronger bond with the Duron than with the NiTi wires.

The ability to utilise the additional extraction force required to initiate first movement in samples under tension will be application dependent. These results illustrate the difficulties faced in the successful adoption of active NiTi structures because of the anisotropic properties of the woven structure and their ability to continually alter tension, not only laterally as in this study, but up to and including a 45 degree bias angle.

4.2.2.4 Summary of results for phase 3, study ii

The results from this study have successfully demonstrated patterns in the interrelationships between different combinations of variables in the woven structures, supporting yarns and integrated NiTi components. Although many clear trends were identified, not all the results were conclusive and a number of areas have been highlighted that will require further investigation to clarify the outcomes. The range of samples and results produced for this study has also been collated as part of a fully searchable database to be used for future investigations.

This study has investigated two key aspects of the integration of NiTi components into textile structures. The first was the influence that the NiTi components had on the flexure and rigidity of the samples, and the second was the extraction force required to initiate first movement of the NiTi components in the structure.

Bend angle testing

Evaluation of differences in rigidity between the samples using the bend angle

This part of the study evaluated the flexibility of NiTi composite textile structures and helped to inform a comparative evaluation of the relationship between the rigidity of a sample and the force required to extract the NiTi components.

Clear patterns of results were obtained from the bend testing:

- The extremes in bend angle seen in the free NiTi were not replicated in the woven samples, indicating the limited influence the selected NiTi had on the bend angle.

- Clear results were obtained across all NiTi components demonstrating a correlation between the supporting yarn and bend angle with the mercerised cotton yarn providing the largest bend angles, followed by the combined cotton and Duron warp, polyester and Kevlar respectively.
- From the correlation between bend angle and supporting yarn it was identified that the more flexible samples (cotton) required lower extraction loads than the stiffer (Kevlar) samples.

Extraction testing

Figure 62 was created to provide an overview of extraction force required to initiate first movement in the samples tested as part of this study. Providing an overview in this way highlights trends that become clearer with closer investigation, as well as those that could later skew the results; for instance, the exceptionally high loads required to remove the additional Kevlar components in both the 30x100mm and the 100x100mm plain weave samples.

Based on the six combinations of variables covered in this study, the following conclusions have been reached:

- When viewed across all the supporting yarns there was a correlation in the results between the bend angle test and those of the extraction to first movement. As the sample bend angle increased, there was a corresponding drop in the load needed to initiate the first movement of the integrated component.
- An increase in bend angle precludes a corresponding drop in the load required to achieve first movement.
- This study has demonstrated a clear hierarchy for the non-heat-set supporting yarns, irrespective of the NiTi component, with cotton requiring the least force followed by Kevlar and polyester respectively.
- The trend for the extraction force from the Duron samples was less clear, although a lower level of Duron in the structure equated to a lower extraction force. However, all the results from the heat-set Duron samples required notably higher extraction forces than the non-heat set samples.
- Direct comparisons of results from this study and phase 2, study iii were of particular interest, showing that when the Duron yarn is placed parallel to the integrated NiTi component, very low extraction forces are recorded, while very high forces are required when the Duron crosses the NiTi component in a perpendicular manner.
- In the heat set Duron samples, the larger surface areas of the ribbons resulted in the highest extraction forces required, whereas the 25x445µm ribbon again resulted in the highest extraction forces for the non-heat set Duron samples, due to its conforming to the woven structure

- In the heat set Duron samples, a correlation was found between an increasing number of warp ends crossing the NiTi and the elevated extraction forces required to initiate first movement.
- Clear proportional increases were recorded as a result of the increase in sample size, with the trends from the 30 x 50 mm samples being mirrored in the 30 x 100 mm ones.
- The results comparing the 30 x 100mm samples, and the 100 x 100mm ones under lateral tension, show the cotton, Kevlar and polyester samples requiring forces comparable to those for heat set Duron.
- Although the 25x445µm ribbon samples required additional force while under tension, it was notably less than for the other NiTi components. This was seen as a result of the warp structure being straightened out, causing a reduction of the distortion usually seen in the fine ribbon.

Appendix B. contains extraction results focusing on the relationship between combinations of specific variables.

4.2.3 Phase 3, study iii: Influence of yarn and weave structure on NiTi wire extraction, using computer controlled tensile / compression testing machines

Focus:
Patterns of extraction
Woven structures
Supporting yarn
Sett of fabric (Kevlar samples only)
Extracted component

  - Cross section and dimensions
  - Surface finish (Kevlar samples only)

Tensile testing of supporting yarns

Evaluation:
Wire extraction tensile test (computer controlled tensile / compression testing machines)

4.2.3.1 Aims and method

The aim was to focus on dynamic, rather than static friction, as in the previous studies. Rather than identifying the peak force needed to overcome the friction between the supporting structure and the inserted NiTi components, dynamic friction demonstrated how the subsequent movement of the integrated component is affected by the variable parameters. An understanding of the dynamic friction between the inserted NiTi component and the supporting structure can be used to control the ease of movement of the inserted component within the structure, thus playing an important role in the development and control of secondary levels of movement.

4.2.3.2 Overview of samples

Due to time constraints, a limited number of samples were chosen for evaluation in study iii, although those selected demonstrated a cross section of parameters that could be compared and evaluated (Table 41). Samples tested were selected covering five of six yarn combinations in study ii; Duron warp cotton weft, was omitted because of the poor quality of samples due to inconsistent heat setting.

Sample	Supporting yarn	epi	Weave	NiTi wire	Sample size
269B-274B	Mercerised cotton	66	Plain weave	*b*	30x50mm
292B-297B		88	2/2 twill		
338B-343B	Kevlar	72	Plain weave	*b*	30x50mm
344B-348B					
361B-366B			2/2 twill		
372B-377B		96			
395B-400B			Plain weave & 2/2 twill		
418B-422B	Polyester		Plain weave	*b*	30x50mm
556B-561B	Duron	54	Plain weave	*b*	30x50mm
573B-578B		72	2/2 twill		
607B-612B	Mercerised cotton & Duron warp. mercerised cotton weft	72	Plain weave	*b*	30x50mm
624B-629B		112	2/2 twill		

b 115µm, 152µm, 25x445µm, 50x420µm, 170x900µm NiTi wires were used.

Table 41 Overview of samples woven for phase 3, study iii.

Although a selection of yarn combinations was tested, the main focus of this study was on the Kevlar samples for which an additional three parameters were investigated (Table 42). The decision to extend the range of Kevlar samples centred on the physical demands of heat and abrasion, likely to be placed on the supporting structure by active shape control over an extended period of time. With its superior heat and abrasion resistive properties, Kevlar supporting structures will be better placed to undergo repeated and prolonged activation. From the other supporting yarn combinations plain weave and 2/2 twill were selected to give the most diverse and transferable results.

	Weave	Sett	NiTi finish
Standard tests	Plain weave	Balanced	As purchased
	2/2 twill	Balanced	As purchased
Additional variables tested	Plain weave	Balanced	**Additional heat treatment**
	2/2 twill	**Under**	As purchased
	Combined weave	Balanced	As purchased

Additional parameters are shown in **bold** type.

Table 42 An extended range of Kevlar samples was tested investigating an additional three parameters.

4.2.3.3 Results

Patterns of extraction

The results of the extraction tests from the Instron test machine were collated and are presented in appendix F. After an initial evaluation of the results, key patterns of extraction were identified. These consisted of three distinct patterns leading up to the peak extraction force (PEF) (Figure 75) and five patterns of extraction after achieving PEF (Figure 76).

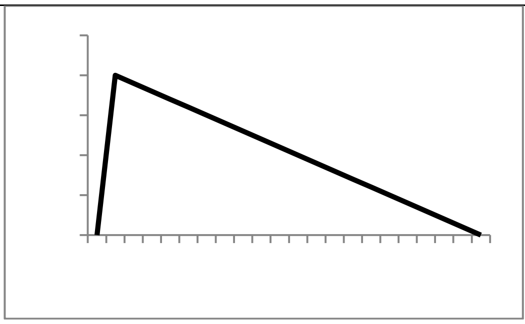
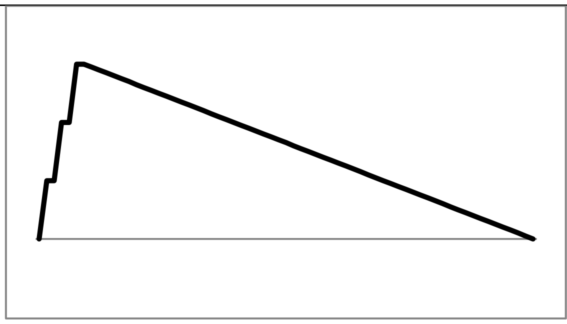
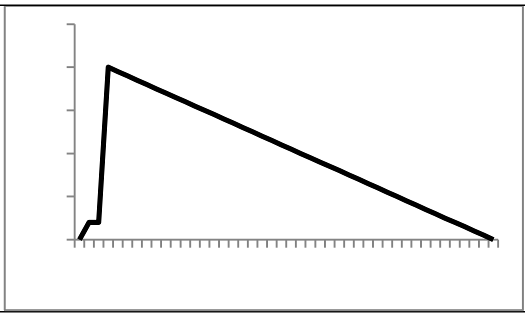
 A. Even increase pattern leads up to PEF	 B. Evenly stepped pattern leads up to PEF
	
C. A distinct stepped pattern leads up to PEF	

Figure 75 Patterns of extraction leading up to peak extraction force (PEF).

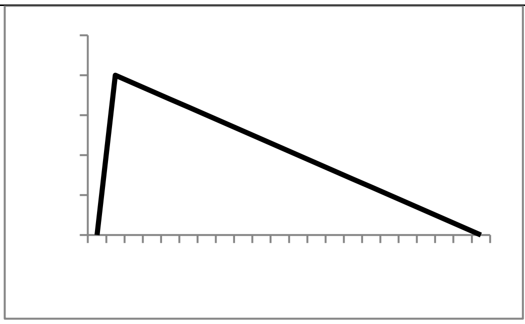
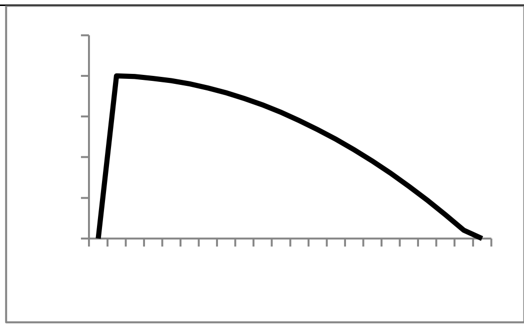
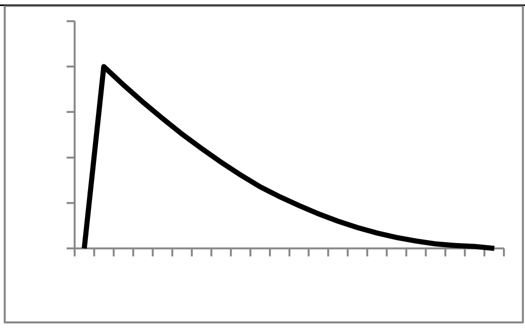
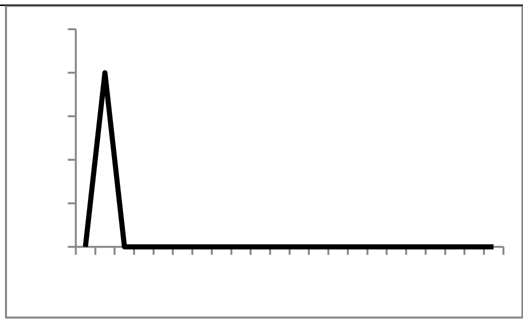
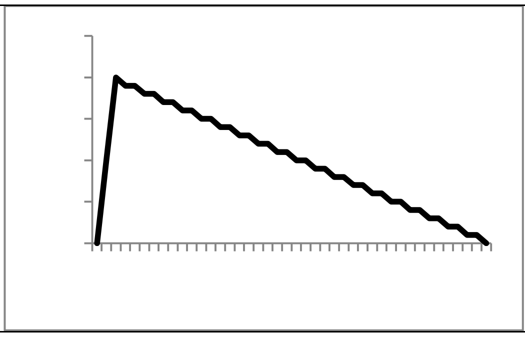
 a. Even increase and decrease of extraction force	 b. After PEF, the force required declined slowly then increased towards full extraction
 c. After PEF the force required initially declined quickly before slowing towards full extraction	 d. After PEF the force required dropped very rapidly to full extraction
 e. After PEF the force required is relatively even but steps down in distinct increments	

Figure 76 Patterns of extraction seen during testing using the Instron tensile test machine.

Shown in Table 43 the trend across the majority of the samples leading up to the PEF is the evenly stepped pattern B (Figure 75). From the results gathered there is no definitive correlation between the patterns of extraction leading up to PEF and the variables investigated in this study (supporting yarn, woven structure and NiTi component). The only exception to the predominance of pattern B (Figure 75) can be seen in the samples woven with a cotton and polypropylene warp which demonstrated a predominance of pattern C (Figure 75) up to PEF. The results from the cotton and polypropylene warp samples demonstrate that the inserted component is held firmly before total failure but it is unclear why these results were not also seen in the samples with 100% polypropylene warp. During the extraction testing, it was noted that the initial movements and stepping, leading up to PEF (Figure 75 B and C), were a result of the straightening and release of the crimp in the inserted component by the woven structure. This stepping never extended for more than 5mm before the PEF was reached and the component was effectively released from the structure. Contrary to usual comparisons of static and dynamic friction, due to the initial release of the crimp, static friction was overcome prior to the PEF. In spite of this delay in reaching PEF the comparison of results from static and dynamic friction demonstrates a correlation across the majority of samples tested (Figure 77).

				Pattern to PEF			After PEF				
				A	B	C	a	b	c	d	e
Cotton supporting yarn	Plain weave	269B	Cotton		X				X		
		270B	115µm		X		X				
		271B	152µm		X		X				X
		272B	25 x 445µm			X			X		
		273B	50 x 420µm			X	X				X
		274B	170 x 90µm			X	X				X
	2/2 Twill	292B	Cotton			X			X		
		293B	115µm		X		X				X
		294B	152µm		X		X				X
		295B	25 x 445µm		X				X		
		296B	50 x 420µm		X		X				X
		297B	170 x 90µm			X	X				X
Kevlar supporting yarn	Plain weave	338B	Kevlar		X					X	
		339B	115µm	X					X		X
		340B	152µm	X			X				X
		341B	25 x 445µm		X				X		
		342B	50 x 420µm		X		X				X
		343B	170 x 90µm			X	X				X
		344B	Heavy oxide 115µm		X				X		X
		345B	Heavy oxide 152µm		X		X				X
		346B	Heavy oxide 25 x 445µm		X				X		
		347B	Heavy oxide 50 x 420µm	X			X				X
		348B	Heavy oxide 170 x 90µm			X	X				X
	2/2twill under sett	361B	Kevlar			X			X		
		362B	115µm	X			X				
		363B	152µm		X		X				X
		364B	25 x 445µm		X				X		
		365B	50 x 420µm		X		X				X
		366B	170 x 90µm		X		X				X
	2/2 twill	372B	Kevlar		X					X	
		373B	115µm			X			X		X
		374B	152µm		X		X				X
		375B	25 x 445µm			X	X				
		376B	50 x 420µm			X	X				
		377B	170 x 90µm			X	X				X
	Combined weave	395B	Kevlar		X				X		
		396B	115µm			X			X		X
		397B	152µm		X		X				X
		398B	25 x 445µm			X	X				
		399B	50 x 420µm		X		X				X
		400B	170 x 90µm		X		X				X
Polyester	Plain weave	418B	Polyester			X			X		
		419B	115µm		X		X				X
		420B	152µm	X			X				X
		421B	25 x 445µm		X				X		
		422B	50 x 420µm	X			X				X
		423B	170 x 90µm	X			X				X
Polypropylene supporting yarn	Plain weave	556B	Cotton		X			X			
		557B	115µm		X			X			
		558B	152µm			X				X	
		559B	25 x 445µm	X						X	
		560B	50 x 420µm	X				X			
		561B	170 x 90µm	X				X			
	2/2 twill	573B	Cotton			X				X	
		574B	115µm		X			X			
		575B	152µm		X			X			
		576B	25 x 445µm		X					X	
		577B	50 x 420µm		X			X			
		578B	170 x 90µm			X	X	X			
Polypropylen and cotton supporting ya	Plain weave	607B	Cotton			X				X	
		608B	115µm			X			X		X
		609B	152µm			X	X				X
		610B	25 x 445µm	X				X			
		611B	50 x 420µm			X			X		X
		612B	170 x 90µm	X			X				X
	2/2 twill	624B	Cotton			X				X	
		625B	115µm			X			X		
		626B	152µm			X	X				X
		627B	25 x 445µm			X			X		
		628B	50 x 420µm			X		X			
		629B	170 x 90µm			X		X			

Table 43 Evaluation of results from dynamic friction tests.

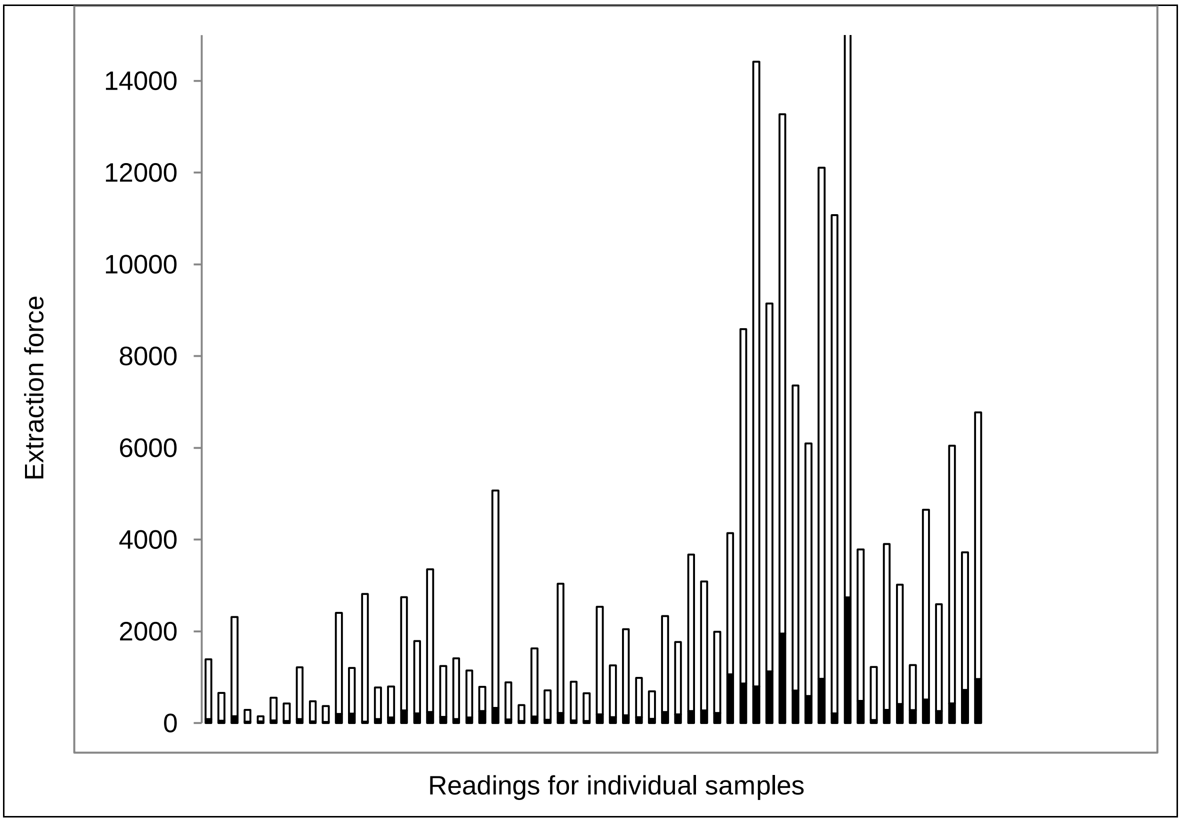


Figure 77 Comparison of results for static and dynamic friction.

After reaching PEF the majority of the extracted NiTi components in the cotton, Kevlar and polyester samples were fully released with an even decrease in force (Figure 76). This indicated that after reaching PEF the component was effectively free from the structure and the decreasing extraction force correlated with the decreasing length of embedded NiTi. The exception to this pattern is the extraction of the yarn and a number of the 115µ wire and 25x445µm ribbons which demonstrated extraction pattern c (Figure 76). The results seen from these finer extracted components indicate that although a greater PEF is reached due to the conformity to the structure of the finer component, on release a rapid initial reduction in force is recorded.

Corresponding with the patterns of extraction leading up to PEF, the samples containing polypropylene yarn demonstrated an alternative dominance of pattern after PEF was reached. Although the thicker 170x900µm NiTi still demonstrated an even reduction in extraction force (Figure 76 a), the larger proportion of the NiTi samples demonstrated extraction pattern b (Figure 76). This extraction pattern denotes a more gradual slowing of extraction force after PEF. During extraction no clear indicators were evident for the dominance of this pattern. The results for the yarn and 25x445µm ribbon and samples that demonstrated pattern d (Figure 75) after PEF were due to the failure and snapping of the component before its release from the structure.

Irrespective of the dominant extraction pattern, the majority of the samples demonstrated a stepping down of extraction force after PEF Figure 76 e) at relatively even increments until full extraction. This regular stepping denoted defined sections where there was a more dramatic drop in the levels of force required as the inserted component was released by the warp threads. This stepping down of the force required for extraction formed a distinct trend in the cotton, Kevlar and polyester samples with the extraction of the supporting yarn and 25x445µm ribbon not demonstrating this characteristic in any of the samples tested. In addition to this major stepped pattern, a finer pattern of increasing and decreasing force was seen (Figure 78). Following further investigation, including the counting of the peaks and troughs, this fine stepped pattern was connected to the release of the inserted component from individual warp threads.

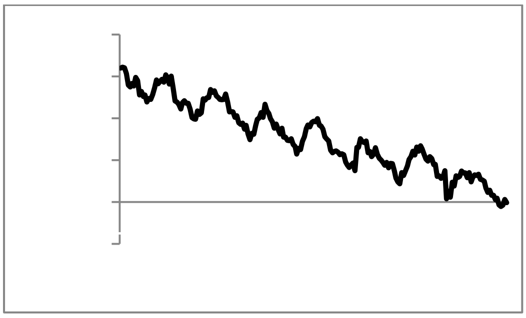


Figure 78 The finer pattern seen during the extraction testing using the Instron tensile test machine showing the release of the inserted NiTi component from the individual warp threads.

4.2.3.4 Summary of results for phase 3, study iii

This study has demonstrated a correlation between the results for dynamic and static friction and the woven structure, and has identified key patterns of extraction both leading up to and after reaching PEF. Although the results from the dynamic friction tests did not demonstrate clear patterns of extraction based on the specific variables, patterns of behaviour were seen across the integrated NiTi components.

The following key points emerged from this study:

- Leading up to PEF two stepped patterns were identified which corresponded with the partial release of the integrated component from the supporting structure prior to full release and reaching PEF. An even stepping to PEF was seen mainly in the cotton, Kevlar and polyester samples, whereas the samples woven with a cotton and polypropylene warp showed a single step before a steady increase to PEF.
- With the stepping never extended for more than 5mm before the PEF these results show that if an initial portion of the integrated component is released from the structure full integrity is not lost.
- With the exception of the yarn and a number of the 115µ wire and 25x445µm ribbons, after reaching PEF the cotton, Kevlar and polyester and the integrated component demonstrated an even decrease in force until it was free from the structure. The results seen for finer extracted wires and ribbons showed rapid initial reduction in force after reaching PEF.
- With the exception of the 170x900µm NiTi, the polypropylene samples demonstrated a gradual decrease extraction force after PEF.

5 Conclusion

This investigation has for the first time demonstrated how the manipulation of simple woven structures can be used to alter the direct and indirect mechanical shape transfer from integrated NiTi components. The initial enquiry contributes to the current body of knowledge by identifying and clearly setting out key variables and parameters that affect the shape transfer and specifically the influence of cloth sett, woven structure and choice of yarn, in combination with a variety of NiTi wires and ribbons. Initial samples demonstrated that lighter, tighter woven structures can attain almost total conformity to the trained NiTi shape, whilst the heavier or looser samples showed minimal conformity. These differences in structure can be located at specific points along the length of a single or multiple integrated NiTi component to effect different levels of shape transfer from uniformly trained wire Figure 52. From this initial proving of concept, the research meticulously investigated and recorded results on the frictional properties and interfacial relationship between different woven structures and NiTi components. The removal of application specific restrictions based on visual, tactile or functional pre-requisites increased the depth of understanding of the potential and limitations of the area, creating a valuable resource that will support future decision making across a diverse range of applications within this emerging design field.

Focusing on the weavability and handle of this composite textile, initial samples demonstrated that although producing viable cloths, the combination of 2/60cc mercerised cotton and 150µm NiTi wire was at the limit of weavability. In these samples the NiTi became very dominant and repeatedly broke out of the structure. It was found that a heavier 2/40cc yarn offered improved weavability when inserting a 150µm NiTi wire and subsequently greater versatility when investigating other design variables. The wires and ribbons used throughout the investigation could all produce good quality samples, although the fine 25x445µm ribbon demonstrated two distinct issues relating to its weavability. The first was a tendency for the NiTi to twist during the beating of the weft. The second, which was particularly seen in over sett structures, was crimping as the NiTi conformed to the interlacements of the warp. By applying a light tension to the wire while beating the NiTi pick and subsequent yarn pick, both these weaving defects could be reduced. The finer NiTi components that easily conform to the interlacements of the woven structure show a corresponding rise in load required to initiate first movement.

Good quality samples can be produced with the fabric both over and under sett, but it was found that when evenly to slightly over sett the NiTi had the most support within the structure without greatly incurring additional cloth weight or loss of structural integrity. Improved weavability and reduced visual impact of the NiTi were achieved by increasing the epi, but when increased to 168epi in the mercerised cotton samples (202% over sett for plain weave) the reduction in picks per inch resulted in the reduced stability of the woven structure. As well as reducing the visual impact, increasing the epi lessened the effect the NiTi had on the cloth’s handle, but this was due to the corresponding increase in cloth weight.

A comparative investigation established that the integration of the finer 115µm wire and 25x445µm ribbon had a limited effect on the handle of the samples whilst the 150µm wire had a noticeable impact. Because the 70x900µm ribbon used was in an *as drawn* state rather than annealed, direct comparisons could not be made with other samples but it would be envisaged that with its increased dimensions it would continue to significantly influence the handle of the cloth even in an annealed state. A further investigation into weavability concentrated on the addition of selvedges and the exiting of the NiTi at this transitioning point. Due to the adaptable nature of the 2/40cc mercerised cotton, when the NiTi exited the cloth only a single replacement pick was required to accommodate both the 115µm and 152µm wires and keep the cloth balance. The increased profile and resultant distortion of the structure meant that the 25x445µm and 170x900µm ribbon required an additional pick of cotton, although care would be needed not to over pack the selvedge.

To understand the influence specific design variables would have on mechanical shape transfer from a NiTi component, two distinct test methods were employed: extraction testing (investigating static and dynamic friction) and bend angle testing (investigating flexibility).The identification of differences in static friction at the point of first movement indicates the level of independence the NiTi has within the woven structure and subsequently the level of mechanical shape transfer that would be expected. Linking closely with the cloth sett, the results demonstrated that a plain weave cloth, which has a high ratio of interlacement to threads within a repeat, required a higher loading to initiate first movement than the corresponding 2/2 twill or satin weave sample which respectively have progressively lower ratios of interlacements to threads. Although the NiTi was held within the plain weave section of the combined weave samples the looser surrounding 2/2 twill structure afforded more movement than plain weave alone and consequentially the results fell between the corresponding full plain and 2/2 twill samples.

Combining the extraction test results with those from the bend angle testing, a correlation was identified based on the supporting yarn. The results showed that more flexible cotton samples required a lower extraction load to initiate the first movement than the corresponding polyester and Kevlar samples which were progressively less flexible samples. This can be seen in the extreme with the heat set polypropylene samples which, due to their rigidity, gave no bend angle reading but required substantially higher loads to initiate first movement. The exceptions to this were the samples where the polypropylene was inserted into the weft and ran parallel to the NiTi. In these samples because of the very limited interfacial contact with the NiTi the polypropylene formed a channel through which the NiTi could move with little resistance.

Due to the holding mechanism of the polypropylene being that of adhesion rather than the friction caused by the interlacements of the yarn these samples demonstrates a number of distinct characteristics. The larger surface area of the ribbons in contact with the polypropylene resulted in the highest extraction loads, whereas in the non heat set samples the conformance to the woven structure resulted in the highest extraction load. Although relating to the number of polypropylene warp ends crossing the NiTi, rather than the structure itself, the results for the different woven structures show a correlation between the increasing and the elevated extraction forces required to initiate first movement, with the lower level of polypropylene in the structure requiring a lower extraction force.

Clear proportional increases were recorded as a result of the increase in sample size, with the trends from the 30 x 50 mm samples being mirrored but raised in the 30 x 100 mm samples. The results comparing the 30 x 100mm samples, and the 100 x 100mm samples under lateral tension, demonstrated substantially higher extraction loads for the cotton, Kevlar and polyester samples which were comparable to those of the heat set polypropylene. An interesting result was seen in the testing of the 25x445µm ribbon under tension where, although an additional force was required to initiate first movement, it was a notably smaller increase compared to the other NiTi components. This was due to the adoption of adhesion as the holding mechanism rather than the usual reliance on the woven structure seen in the fine ribbon, which brought it in line with the other ribbons.

5.1 Future research

The emerging field of active shape memory textiles should not be viewed in isolation but as an integral part of a wider classification of flexible materials that can demonstrate forms of active shape control. This research has highlighted the ability to develop increasingly complex and diverse patterns of movement from uniformly trained NiTi components in complex woven structures, rather than the need to accurately place complex trained NiTi components in uniformed structures. Opening up a wider range of applications, this shift in understanding of shape transfer offers exciting new possibilities for a variety of disciplines including apparel, medical, aerospace, architecture and engineering. Cataloguing the results has created an extensive technical database that is searchable by single or multiple design variables. This database is a valuable resource that will support future decision making within this emerging design field.

The surface properties of the integrated NiTi can be further investigated. A greater understanding is required of the influence and role the surface finish of the NiTi can have in direct shape transfer to different structures and also how it can be used to initiate indirect shape transfer. In particular, when considering its movement within the woven structure during indirect shape transfer the question of fibre damage and fatigue resulting in the failure of surrounding threads will also need to be investigated. As has been seen with the woven structure the surface finish of a NiTi wire has the potential to be altered along its length. Presenting different surface conditions to the supporting structure could be a way to either increase the grip of the textile on the NiTi or allow greater freedom of movement whilst minimising the damage to the surrounding fibres.

Further variables in woven structure can be investigated for the control and shape transfer of NiTi through the use of Jacquard and 3D woven structures. These would offer greater levels of freedom in the development of the composite and placement of the NiTi component. 3D woven structures would allow for additional dimensionality, creating complex structures where functionality can be inserted at different levels. The activation, control and cyclic performance of integrated NiTi components within the woven structures by either changes in ambient temperature, or resistive heating will require specific investigation. This will be especially important if long lengths of wire are being used.

The continued development of SMP and EAP will mean they become an increasingly attractive alternative to NiTi for the design of active textiles. Even though distinct differences will exist in the relationship between interaction of SMA and SMP components, many of the variables and basic design principles relating to levels of direct and indirect shape transfer investigated in this thesis will be pertinent.

The area of active textiles is still in its infancy and as such there is the potential for a wide range of application focused research across a variety of disciplines, enhancing existing devices such as cardio vascular stent grafts as well as opening up new areas. The ability to dynamically control active textiles through the manipulation of individual weave variables in addition to superelastic and thermal shape memory will facilitate the development of complex, multifunctional devices, integrating support, sensing and actuation into single cohesive woven structures.

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Appendices

Appendices B and E are attached are presented here. Appendices A, C and D are available from the author (p.dyer@brighton.ac.uk).

Here follows a brief outline of their content:

Appendix A: Overview of areas covered by this thesis and position within the broader field of knowledge.

Presented in Adobe PDF file format, appendix A is a diagrammatic representation of the broad area of research relating to the dynamic control of active textiles. To aid cross-referencing areas discussed in this thesis are identified with relevant chapter references.

Appendix B: Tabulation of variables relating to the woven samples including extraction test results.

Presented here appendix B. sets out in a comparative table form, the specific variables relating to samples woven as part of this study.

Appendix C: Searchable Database of sample properties and results.

Presented in Filemaker Pro file format appendix C. provides detailed profiles of the constituent properties and production methods of each woven sample. Developed as a fully searchable database, any of the fields or combination of fields can be searched and presented in a variety of formats. The searchable database has resulted in a valuable resource capable of informing future research.

Appendix D: Sample sheets.

Presented in Adobe PDF file format appendix D. is converted from the 'form view' of the Filemaker Pro database (appendix C.). The sample sheets have been included in the Adobe PDF format due to its open access status across operating systems using Adobe acrobat reader (downloadable from www.adobe.com/products/reader), Converting the file to PDF looses the search capabilities of the Filemaker Pro format as well as some image quality.

Appendix E: Dynamic friction results from the Instron tensile test machine.

Presented here as line charts from the results gathered from the extraction testing using the Instron test machine.

Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Dimentions	100 / 100 mm																			
Cotton Merc.	X	X	X	X	X	X	X		Warp					X	X	X	X	X	X	X
Viscose									Weft											
Polyester multi-filament																				
Plain weave			X			X			X	X		X		X	X		X	X		
2/2 twill				X			X						X			X				
Plain & 2/2 twill	X	X			X			X			X								X	X
84 epi 2/60cc	X	X	X																	
72 epi 2/40cc				X	X	X	X	X	X	X	X	X	X	X	X	X				
120 epi 2/40cc																	X	X	X	X
168 epi 2/40cc																				
144 epi 2/40cc																				
100µ		X	X	X							X	X	X	X	X	X	X		X	
115µ																				
150µ	X				X	X	X	X	X	X								X		X
25µ x 445µ																				
170µ x 900µ																				
Oxide	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Pickled																				
As Drawn																				
Fully Annaled																				

Sample no.	21	22	23	24	25	26	27	28	29	30	31	32	32	33	33	34	34	35	35
Dimentions																			
Cotton Merc.	X	X	X	X	X	X	X	X	X										
Viscose																			
Polyester multi-filament										X	X	X	X	X	X	X	X	X	X
Plain weave			X	X	X					X	X	X	X	X	X	X	X	X	X
2/2 twill	X	X				X	X												
Plain & 2/2 twill								X	X										
84 epi 2/60cc																			
72 epi 2/40cc																			
120 epi 2/40cc	X	X	X							X	X	X	X	X	X	X	X	X	X
168 epi 2/40cc				X	X	X	X	X	X										
144 epi 2/40cc																			
100µ	X		X	X		X		X			X								
115µ												X	X						
150µ		X			X		X		X					X	X				
25µ x 445µ																X	X		
170µ x 900µ																		X	X
Oxide	X	X	X	X	X	X	X	X	X		X			X	X	X	X	X	X
Pickled												X	X						
As Drawn																		X	X
Fully Annaled												X	X			X	X		

Sample no.	36	37	38	39	40	41	42	42	43	43	44	45	46	47	48	48	49	50	51	52	53	54
Dimentions																						
Cotton Merc.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Viscose																						
Polyester multi-filament																						
Plain weave	X	X	X	X	X	X	X	X	X	X												
2/2 twill											X	X	X	X	X	X	X	X	X	X	X	X
Plain & 2/2 twill																						
84 epi 2/60cc																						
72 epi 2/40cc																						
120 epi 2/40cc	X																					
168 epi 2/40cc																						
144 epi 2/40cc		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
100µ			X	X								X						X				
115µ					X								X						X			
150µ						X								X						X		
25µ x 445µ							X	X							X	X					X	
170µ x 900µ									X	X							X					X
Oxide			X	X		X	X	X	X	X		X		X	X	X	X	X		X	X	X
Pickled					X								X						X			
As Drawn									X	X							X					X
Fully Annaled					X		X	X					X		X	X			X		X	

Sample no.	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
Dimentions	100 x 100 mm																			
Cotton Merc.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Viscose																				
Polyester multi-filament																				
Plain weave																				
2/2 twill	X	X																		
Plain & 2/2 twill			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
72 epi 2/40cc																				
144 epi 2/40cc	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
168 epi 2/40cc																				
100µ			X					X						X					X	
115µ				X					X						X					X
150µ					X					X						X				
152µ																				
25µ x 445µ	X					X					X						X			
50µ x 420µ																				
170µ x 900µ		X					X					X						X		
Oxide	X	X	X		X	X	X	X		X	X	X		X		X	X	X	X	
Pickled				X					X						X					X
As Drawn		X					X					X						X		
Fully Annaled	X			X		X			X		X				X		X			X
Bend angle																				
Load to first movement																				

Sample no.	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94
Dimentions									50 x 30 mm											
Cotton Merc.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Viscose																				
Polyester multi-filament																				
Plain weave					X	X			X	X	X	X	X	X	X	X	X	X		
2/2 twill							X												X	X
Plain & 2/2 twill	X	X	X	X				X												
72 epi 2/40cc														X	X	X	X	X		
144 epi 2/40cc	X	X	X	X	X	X	X	X	X	X	X	X	X						X	X
168 epi 2/40cc																				
100µ																				
115µ									X					X					X	
150µ	X																			
152µ										X					X					X
25µ x 445µ		X									X					X				
50µ x 420µ												X					X			
170µ x 900µ			X										X					X		
Oxide	X	X	X							X	X	X	X		X	X	X	X		X
Pickled									X					X					X	
As Drawn			X										X					X		
Fully Annaled		X							X	X	X	X		X	X	X	X		X	X
Bend angle									50	47	60	56		40	37	44	57		41	46
Load to first movement									106	59	87	54	58	116	63	145	57	47	71	48

Sample no.	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114
Dimentions																			100 x 100mm	
Cotton Merc.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Viscose																				
Polyester multi-filament																				
Plain weave									X								X			
2/2 twill	X	X	X																	
Plain & 2/2 twill				X	X	X	X	X		X	X	X	X	X	X	X		X	X	X
72 epi 2/40cc																				
144 epi 2/40cc	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
168 epi 2/40cc																				
100µ																				
115µ				X					X					X						
150µ																				
152µ					X					X					X					
25µ x 445µ	X					X					X					X				
50µ x 420µ		X					X					X					X			
170µ x 900µ			X					X					X					X		
Oxide	X	X	X		X	X	X	X		X	X	X	X		X	X	X	X		
Pickled				X					X					X						
As Drawn			X					X										X		
Fully Annaled	X	X		X	X	X	X		X	X	X	X		X	X	X	X			
Bend angle	55	50		10	14	22	18		13	48	62	48		6	10	11	9			
Load to first movement	127	313	39	128	78	169	69	43	64	46	75	47	61	106	66	182	51	65		

Sample no.	115	116	117	118	119	120	121	122	123	124	125
Dimentions	50 x 30 mm										
Cotton Merc.	x	x	x	x	x	x	x	x	x	x	x
Kevlar											
Dacron											
Duron Cl											
Plain weave	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill											
5 end Satin											
plain & 2/2 Twill											
72 epi	x	x	x	x	x	x	x	x	x	x	x
96 epi											
144 epi											
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	46	46	38	57	44		47	45	49	51	
Load to first movement	385	40	56	213	35	37	61	54	162	35	37

Sample no.	126	127	128	129	130	131	132	133	134	135	136
Dimentions											
Cotton Merc.	x	x	x	x	x	x	x	x	x	x	x
Kevlar											
Dacron											
Duron Cl											
Plain weave	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill											
5 end Satin											
plain & 2/2 Twill											
72 epi											
96 epi	x	x	x	x	x	x	x	x	x	x	x
144 epi											
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	47	39	45	45	48		39	40	40	48	
Load to first movement	246	129	62	136	39	344	74	75	245	38	35

Sample no.	137	138	139	140	141	142	143	144	145	146	147
Dimentions											
Cotton Merc.	x	x	x	x	x	x	x	x	x	x	x
Kevlar											
Dacron											
Duron Cl											
Plain weave	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill											
5 end Satin											
plain & 2/2 Twill											
72 epi											
96 epi											
144 epi	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	40	44	40	45	58		43	44	52	53	
Load to first movement	645	81	78	73	23	78	91	78	132	38	44

Sample no.	148	149	150	151	152	153	154	155	156	157	158
Dimentions											
Cotton Merc.	x	x	x	x	x	x	x	x	x	x	x
Kevlar											
Dacron											
Duron Cl											
Plain weave											
2/2 Twill	x	x	x	x	x	x	x	x	x	x	x
5 end Satin											
plain & 2/2 Twill											
72 epi	x	x	x	x	x	x	x	x	x	x	x
96 epi											
144 epi											
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle											
Load to first movement											

Sample no.	159	160	161	162	163	164	165	166	167	168	169
Dimentions											
Cotton Merc.	x	x	x	x	x	x	x	x	x	x	x
Kevlar											
Dacron											
Duron Cl											
Plain weave											
2/2 Twill	x	x	x	x	x	x	x	x	x	x	x
5 end Satin											
plain & 2/2 Twill											
72 epi											
96 epi											
144 epi	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	50	45	53	54	52		44	39	49	46	
Load to first movement	167	81	41	208	42	59	70	48	221	51	42

Sample no.	170	171	172	173	174	175	176	177	178	179	180
Dimentions											
Cotton Merc.	x	x	x	x	x	x	x	x	x	x	x
Kevlar											
Dacron											
Duron Cl											
Plain weave											
2/2 Twill											
5 end Satin											
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x
72 epi	x	x	x	x	x	x	x	x	x	x	x
96 epi											
144 epi											
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle											
Load to first movement											

Sample no.	181	182	183	184	185	186	187	188	189	190	191
Dimentions											
Cotton Merc.	x	x	x	x	x	x	x	x	x	x	x
Kevlar											
Dacron											
Duron Cl											
Plain weave											
2/2 Twill											
5 end Satin											
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x
72 epi											
96 epi											
144 epi	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	57	49	48	58	51		45	44	55	50	
Load to first movement	287	71	40	99	49	42	262	62	107	41	43

Sample no.	192	193	194	195	196	197	198	199	200	201	202
Dimentions											
Cotton Merc.	x	x	x	x	x	x	x	x	x	x	x
Kevlar											
Dacron											
Duron Cl											
Plain weave											
2/2 Twill											
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x
72 epi	x	x	x	x	x	x	x	x	x	x	x
96 epi											
144 epi											
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle											
Load to first movement											

Sample no.	203	204	205	206	207	208	209	210	211	212	213
Dimentions	50 x 30 mm										
Cotton Merc.	x	x	x	x	x	x	x	x	x	x	x
Kevlar											
Dacron											
Duron Cl											
Plain weave											
2/2 Twill											
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x
72 epi											
96 epi											
144 epi	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	47	40	44	45	49		50	40	51	41	
Load to first movement	322	70	66	112	30	187	65	53	170	55	104

Sample no.	214	215	216	217	218	219	220	221	222	223	224
Dimentions											
Cotton Merc.	Twill picks only										
Kevlar											
Dacron											
Duron Cl	Plain weave picks only										
Plain weave											
2/2 Twill											
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x
72 epi	x	x	x	x	x	x	x	x	x	x	x
96 epi											
144 epi											
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	26	17	30	30	31		25	22	33	26	
Load to first movement	691	88	36	242	33	16	97	56	257	40	27

Sample no.	225	226	227	228	229	230	231	232	233	234	235
Dimentions											
Cotton Merc.											
Kevlar											
Dacron											
Duron Cl											
Plain weave											
2/2 Twill											
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x
72 epi											
96 epi											
144 epi	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	53	54	45	53	64		43	46	47	55	
Load to first movement	368	58	33	39	19	19	23	31	51	21	46

Sample no.	236	237	238	239	240	241	242	243	244	245	246
Dimentions											
Cotton Merc.	Warp										
Kevlar											
Dacron											
Duron Cl	Weft										
Plain weave	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill											
plain & 2/2 Twill											
72 epi	x	x	x	x	x	x	x	x	x	x	x
96 epi											
144 epi											
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	27		21	20	23			18	22	20	
Load to first movement	711	41	28	88	29	20	33	20	223	26	62

Sample no.	247	248	249	250	251	252	253	254	255	256	257
Dimentions											
Cotton Merc.											
Kevlar											
Dacron											
Duron Cl											
Plain weave	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill											
plain & 2/2 Twill											
72 epi											
96 epi	x	x	x	x	x	x	x	x	x	x	x
144 epi											
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle											
Load to first movement											

Sample no.	258	259	260	261	262	263	264	265	266	267	268
Dimentions											
Cotton Merc.											
Kevlar											
Dacron											
Duron Cl											
Plain weave	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill											
plain & 2/2 Twill											
72 epi											
96 epi											
144 epi	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x				
152µ Ø			x					x			
25x445µ				x					x		
50x420µ					x					x	
170 x900µ						x					x
Heavy Oxide							x	x	x	x	x
Oxide			x	x	x	x					
Pickled		x									
Fully Annealed		x	x	x	x						
Work hardened						x					
Bend angle	42	21	39	38	35		20	29	37	36	
Load to first movement	173	39	18	53	32	23	57	49	118	114	20

Sample no.	Dimentions	Cotton Merc.	Kevlar	Dacron	Duron Cl	Plain weave	2/2 Twill	plain & 2/2 Twill	66.67 epi	88 epi	115µ Ø	152µ Ø	25x445µ	50x420µ	170 x900µ	Heavy Oxide	Oxide	Pickled	Fully Annealed	Work hardened	Bend angle	Load to first movement
269	50 x 30mm	X				X			X												59	135
270	50 x 30mm	X				X			X		X							X	X		51	85
271	50 x 30mm	X				X			X			X					X		X		40	50
272	50 x 30mm	X				X			X				X				X		X		55	148
273	50 x 30mm	X				X			X					X			X		X		52	28
274	50 x 30mm	X				X			X						X		X			X		40
275	50 x 30mm	X				X			X		X					X					46	47
276	50 x 30mm	X				X			X			X				X					46	52
277	50 x 30mm	X				X			X				X			X					54	142
278	50 x 30mm	X				X			X					X		X					52	34
279	50 x 30mm	X				X			X						X	X						45
280	100 x 30 mm	X				X			X												59	239
281	100 x 30 mm	X				X			X		X							X	X		49	166
282	100 x 30 mm	X				X			X			X					X		X		44	97
283	100 x 30 mm	X				X			X				X				X		X		53	222
284	100 x 30 mm	X				X			X					X			X		X		50	97
285	100 x 30 mm	X				X			X						X		X			X		80
286	100 x 100mm	X				X			X												56	702
287	100 x 100mm	X				X			X		X							X	X		48	1171
288	100 x 100mm	X				X			X			X					X		X		50	499
289	100 x 100mm	X				X			X				X				X		X		66	346
290	100 x 100mm	X				X			X					X			X		X		47	639
291	100 x 100mm	X				X			X						X		X			X		668
292	50 x 30mm	X					X			X											45	205
293	50 x 30mm	X					X			X	X							X	X		48	56
294	50 x 30mm	X					X			X		X					X		X		52	43
295	50 x 30mm	X					X			X			X				X		X		53	85
296	50 x 30mm	X					X			X				X			X		X		51	39
297	50 x 30mm	X					X			X					X		X			X		27
298	50 x 30mm	X					X			X	X					X					48	53
299	50 x 30mm	X					X			X		X				X					52	30
300	50 x 30mm	X					X			X			X			X					53	132
301	50 x 30mm	X					X			X				X		X					51	21
302	50 x 30mm	X					X			X					X	X						93
303	100 x 30 mm	X					X			X											45	80
304	100 x 30 mm	X					X			X	X							X	X		48	121
305	100 x 30 mm	X					X			X		X					X		X		52	66
306	100 x 30 mm	X					X			X			X				X		X		53	156
307	100 x 30 mm	X					X			X				X			X		X		51	35
308	100 x 30 mm	X					X			X					X		X			X		51
309	100 x 100mm	X					X			X											51	622
310	100 x 100mm	X					X			X	X							X	X		49	434
311	100 x 100mm	X					X			X		X					X		X		48	539
312	100 x 100mm	X					X			X			X				X		X		51	396
313	100 x 100mm	X					X			X				X			X		X		49	456
314	100 x 100mm	X					X			X					X		X			X		640
315	50 x 30mm	X						X		X											53	117
316	50 x 30mm	X						X		X	X							X	X		43	54
317	50 x 30mm	X						X		X		X					X		X		52	61
318	50 x 30mm	X						X		X			X				X		X		49	95
319	50 x 30mm	X						X		X				X			X		X		51	39
320	50 x 30mm	X						X		X					X		X			X		71
321	50 x 30mm	X						X		X	X					X					43	63
322	50 x 30mm	X						X		X		X				X					52	44
323	50 x 30mm	X						X		X			X			X					49	81
324	50 x 30mm	X						X		X				X		X					51	32
325	50 x 30mm	X						X		X					X	X						65
326	100 x 30 mm	X						X		X											53	442
327	100 x 30 mm	X						X		X	X							X	X		43	145
328	100 x 30 mm	X						X		X		X					X		X		52	120
329	100 x 30 mm	X						X		X			X				X		X		49	137
330	100 x 30 mm	X						X		X				X			X		X		51	56
331	100 x 30 mm	X						X		X					X		X			X		111
332	100 x 100mm	X						X		X											55	766
333	100 x 100mm	X						X		X	X							X	X			338
334	100 x 100mm	X						X		X		X					X		X		51	471
335	100 x 100mm	X						X		X			X				X		X		52	535
336	100 x 100mm	X						X		X				X			X		X		52	360
337	100 x 100mm	X						X		X					X		X			X		356

Sample no.	Dimentions	Cotton Merc.	Kevlar	Dacron	Duron Cl	Plain weave	2/2 Twill	plain & 2/2 Twill	72 epi	96 epi	115µ Ø	152µ Ø	25x445µ	50x420µ	170 x900µ	Heavy Oxide	Oxide	Pickled	Polished	Fully Annealed	Programmed	Work hardened	Bend angle	Load to first movement
338	50 x 30mm		X			X			X														9	330
339	50 x 30mm		X			X			X		X							X		X			10	200
340	50 x 30mm		X			X			X			X					X			X			14	207
341	50 x 30mm		X			X			X				X				X			X			12	29
342	50 x 30mm		X			X			X					X			X			X			18	87
343	50 x 30mm		X			X			X						X		X					X		123
344	50 x 30mm		X			X			X		X					X							10	276
345	50 x 30mm		X			X			X			X				X							14	209
346	50 x 30mm		X			X			X				X			X							12	242
347	50 x 30mm		X			X			X					X		X							18	133
348	50 x 30mm		X			X			X						X	X								88
349	100 x 30 mm		X			X			X														9	2097
350	100 x 30 mm		X			X			X		X							X		X			10	425
351	100 x 30 mm		X			X			X			X					X			X			14	303
352	100 x 30 mm		X			X			X				X				X			X			12	437
353	100 x 30 mm		X			X			X					X			X			X			18	184
354	100 x 30 mm		X			X			X						X		X					X		258
355	100 x 100mm		X			X			X														14	2177
356	100 x 100mm		X			X			X		X							X		X			16	610
357	100 x 100mm		X			X			X			X					X			X			20	872
358	100 x 100mm		X			X			X				X				X			X			17	637
359	100 x 100mm		X			X			X					X			X			X			16	681
360	100 x 100mm		X			X			X						X		X					X		1072
361	50 x 30mm		X				X		X														9	993
362	50 x 30mm		X				X		X		X							X		X			10	121
363	50 x 30mm		X				X		X			X					X			X			15	260
364	50 x 30mm		X				X		X				X				X			X			7	331
365	50 x 30mm		X				X		X					X			X			X			4	83
366	50 x 30mm		X				X		X						X		X					X		43
367	50 x 30mm		X				X		X		X					X							10	136
368	50 x 30mm		X				X		X			X				X							15	81
369	50 x 30mm		X				X		X				X			X							7	210
370	50 x 30mm		X				X		X					X		X							4	59
371	50 x 30mm		X				X		X						X	X								49
372	50 x 30mm		X				X			X													6	885
373	50 x 30mm		X				X			X	X							X		X			12	146
374	50 x 30mm		X				X			X		X					X			X			12	69
375	50 x 30mm		X				X			X			X				X			X			7	222
376	50 x 30mm		X				X			X				X			X			X			18	57
377	50 x 30mm		X				X			X					X		X					X		47
378	50 x 30mm		X				X			X	X					X							12	138
379	50 x 30mm		X				X			X		X				X							12	80
380	50 x 30mm		X				X			X			X			X							7	204
381	50 x 30mm		X				X			X				X		X							18	88
382	50 x 30mm		X				X			X					X	X								70
383	100 x 30 mm		X				X			X													12	605
384	100 x 30 mm		X				X			X	X							X		X			12	304
385	100 x 30 mm		X				X			X		X					X			X			12	179
386	100 x 30 mm		X				X			X			X				X			X			7	370
387	100 x 30 mm		X				X			X				X			X			X			18	199
388	100 x 30 mm		X				X			X					X		X					X		197
389	100 x 100mm		X				X			X													14	1919
390	100 x 100mm		X				X			X	X							X		X			20	462
391	100 x 100mm		X				X			X		X					X			X			16	458
392	100 x 100mm		X				X			X			X				X			X			10	644
393	100 x 100mm		X				X			X				X			X			X			22	
394	100 x 100mm		X				X			X					X		X					X		865
395	50 x 30mm		X					X		X													10	555
396	50 x 30mm		X					X		X	X							X		X			14	189
397	50 x 30mm		X					X		X		X					X			X			11	131
398	50 x 30mm		X					X		X			X				X			X			13	171
399	50 x 30mm		X					X		X				X			X			X			14	125
400	50 x 30mm		X					X		X					X		X					X		91
401	50 x 30mm		X					X		X	X					X							14	184
402	50 x 30mm		X					X		X		X				X							11	129
403	50 x 30mm		X					X		X			X			X							13	224
404	50 x 30mm		X					X		X				X		X							14	169
405	50 x 30mm		X					X		X					X	X								104
406	100 x 30 mm		X					X		X													10	369
407	100 x 30 mm		X					X		X	X							X		X			14	373
408	100 x 30 mm		X					X		X		X					X			X			11	189
409	100 x 30 mm		X					X		X			X				X			X			13	280
410	100 x 30 mm		X					X		X				X			X			X			14	162
411	100 x 30 mm		X					X		X					X		X					X		159
412	100 x 100mm		X					X		X													16	2834
413	100 x 100mm		X					X		X	X							X		X			14	576
414	100 x 100mm		X					X		X		X					X			X			11	769
415	100 x 100mm		X					X		X			X				X			X			20	650
416	100 x 100mm		X					X		X				X			X			X			10	899
417	100 x 100mm		X					X		X					X		X					X		1132

Sample no.	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440
Dimentions	50 x 30mm											100 x 30 mm						100 x 100mm					
Cotton Merc.																							
Kevlar																							
Dacron	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Duron CI																							
Plain weave	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill																							
plain & 2/2 Twill																							
72 epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x						x						x				
152µ Ø			x					x						x						x			
25x445µ				x					x						x						x		
50x420µ					x					x						x						x	
170 x900µ						x					x						x						x
Heavy Oxide							x	x	x	x	x												
Oxide			x	x	x	x								x	x	x	x			x	x	x	x
Pickled		x											x						x				
Fully Annealed		x	x	x	x								x	x	x	x			x	x	x	x	
Work hardened						x											x						x
Bend angle												26	24	29	31	33							
Load to first movement	502	241	189	259	275	217	235	208	32	288	180	481	311	529	331	475	385	1087	598	1054	771	699	1316

Sample no.	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463
Dimentions	50 x 30mm											100 x 30 mm						100 x 100mm					
Cotton Merc.																							
Kevlar																							
Dacron	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Duron CI																							
Plain weave																							
2/2 Twill	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
plain & 2/2 Twill																							
72 epi																							
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x						x						x				
152µ Ø			x					x						x						x			
25x445µ				x					x						x						x		
50x420µ					x					x						x						x	
170 x900µ						x					x						x						x
Heavy Oxide							x	x	x	x	x												
Oxide			x	x	x	x								x	x	x	x			x	x	x	x
Pickled		x											x						x				
Fully Annealed		x	x	x	x								x	x	x	x			x	x	x	x	
Work hardened						x											x						x
Bend angle												23	26	40	41	31		25	18	16	14	23	
Load to first movement	385	202	175	352	137	234	170	181	292	190	157	420	357	327	240	313	349			564	560	494	944

Sample no.	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486
Dimentions	50 x 30mm											100 x 30 mm						100 x 100mm					
Cotton Merc.																							
Kevlar																							
Dacron	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Duron CI																							
Plain weave																							
2/2 Twill																							
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
72 epi																							
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x						x						x				
152µ Ø			x					x						x						x			
25x445µ				x					x						x						x		
50x420µ					x					x						x						x	
170 x900µ						x					x						x						x
Heavy Oxide							x	x	x	x	x												
Oxide			x	x	x	x								x	x	x	x			x	x	x	x
Pickled		x											x						x				
Fully Annealed		x	x	x	x								x	x	x	x			x	x	x	x	
Work hardened						x											x						x
Bend angle												24	26	16	28	32		16	19	18	11	13	
Load to first movement	297	232	223	288	234	187	228	338	279	177	224	432	348	247	34	380	361	679	995	568	452	1059	1072

Sample no.	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509
Dimentions	50 x 30mm											100 x 30 mm						100 x 100mm					
Cotton Merc.	Weft																						
Kevlar																							
Dacron																							
Duron CI	Warp																						
Plain weave	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill																							
plain & 2/2 Twill																							
60 epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
78 epi																							
115µ Ø		x					x						x						x				
152µ Ø			x					x						x						x			
25x445µ				x					x						x						x		
50x420µ					x					x						x						x	
170 x900µ						x					x						x						x
Heavy Oxide							x	x	x	x	x												
Oxide			x	x	x	x								x	x	x	x			x	x	x	x
Pickled		x											x						x				
Fully Annealed		x	x	x	x								x	x	x	x			x	x	x	x	
Work hardened						x											x						x
Bend angle																							
Load to first movement												713	503	712	350	573	5353	2003	1172	877	1624	1866	

Sample no.	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532
Dimentions	50 x 30mm											100 x 30 mm						100 x 100mm					
Cotton Merc.																							
Kevlar																							
Dacron																							
Duron CI																							
Plain weave																							
2/2 Twill	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
plain & 2/2 Twill																							
60 epi																							
78 epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x						x						x				
152µ Ø			x					x						x						x			
25x445µ				x					x						x						x		
50x420µ					x					x						x						x	
170 x900µ						x					x						x						x
Heavy Oxide							x	x	x	x	x												
Oxide			x	x	x	x								x	x	x	x			x	x	x	x
Pickled		x											x						x				
Fully Annealed		x	x	x	x								x	x	x	x			x	x	x	x	
Work hardened						x											x						x
Bend angle																							
Load to first movement	782	647		528	987	2561	520	275	1256	563		624	572	546	1672	1190	3613	737		1025	1050	1766	

Sample no.	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555
Dimentions	50 x 30mm											100 x 30 mm						100 x 100mm					
Cotton Merc.																							
Kevlar																							
Dacron																							
Duron CI																							
Plain weave																							
2/2 Twill																							
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
60 epi																							
78 epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x						x						x				
152µ Ø			x					x						x						x			
25x445µ				x					x						x						x		
50x420µ					x					x						x						x	
170 x900µ						x					x						x						x
Heavy Oxide							x	x	x	x	x												
Oxide			x	x	x	x								x	x	x	x			x	x	x	x
Pickled		x											x						x				
Fully Annealed		x	x	x	x								x	x	x	x			x	x	x	x	
Work hardened						x											x						x
Bend angle																							
Load to first movement	661	518	529	392	232	3000	517	614	545	1216	2420	665	583	652	269	199	5027	694	844	954	856	1672	1646

Sample no.	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572
Dimentions	50 x 30mm											100 x 30 mm					
Cotton Merc.																	
Kevlar																	
Dacron																	
Duron Cl	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Plain weave	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill																	
plain & 2/2 Twill																	
54 epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
72 epi																	
115µ Ø		x					x						x				
152µ Ø			x					x						x			
25x445µ				x					x						x		
50x420µ					x					x						x	
170 x900µ						x					x						x
Heavy Oxide							x	x	x	x	x						
Oxide			x	x	x	x								x	x	x	x
Oxide Free		x											x				
Fully Annealed		x	x	x	x								x	x	x	x	
Work hardened						x											x
Bend angle																	
Load to first movement	672	1062	861	797	1125	1949	824	594	965	830	1401	761	743	556	826	1018	2525

Sample no.	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589
Dimentions	50 x 30mm											100 x 30 mm					
Cotton Merc.																	
Kevlar																	
Dacron																	
Duron Cl	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Plain weave																	
2/2 Twill	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
plain & 2/2 Twill																	
54 epi																	
72 epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x						x				
152µ Ø			x					x						x			
25x445µ				x					x						x		
50x420µ					x					x						x	
170 x900µ						x					x						x
Heavy Oxide							x	x	x	x	x						
Oxide			x	x	x	x								x	x	x	x
Oxide Free		x											x				
Fully Annealed		x	x	x	x								x	x	x	x	
Work hardened						x											x
Bend angle																	
Load to first movement	753	705	590	967	214	2736	732	794	967	917	1917	742	842	519	1435	1035	3991

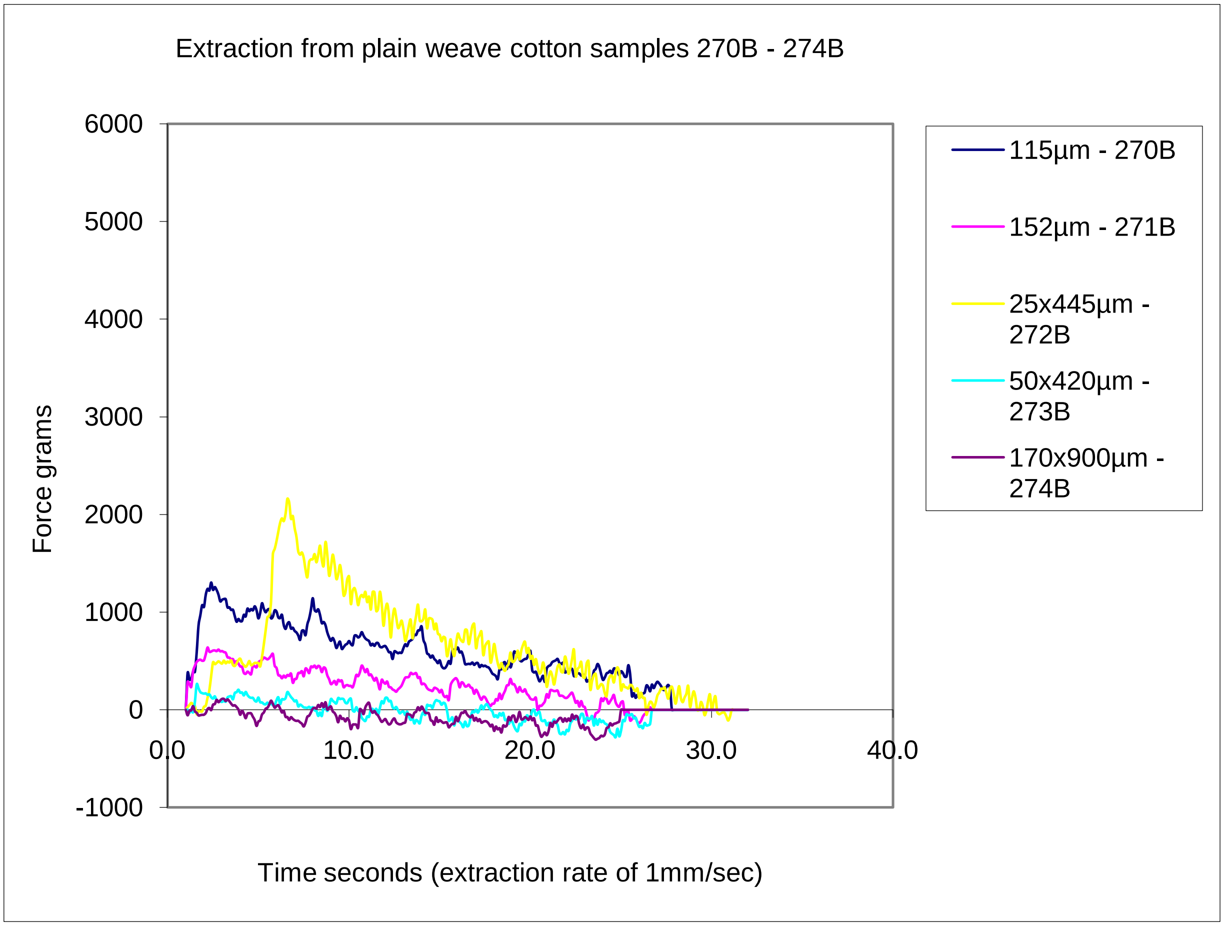
Sample no.	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606
Dimentions	50 x 30mm											100 x 30 mm					
Cotton Merc.																	
Kevlar																	
Dacron																	
Duron Cl	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Plain weave																	
2/2 Twill																	
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
54 epi																	
72 epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x						x				
152µ Ø			x					x						x			
25x445µ				x					x						x		
50x420µ					x					x						x	
170 x900µ						x					x						x
Heavy Oxide							x	x	x	x	x						
Oxide			x	x	x	x								x	x	x	x
Oxide Free		x											x				
Fully Annealed		x	x	x	x								x	x	x	x	
Work hardened						x											x
Bend angle																	
Load to first movement	740	473	435	676	105	2513	942	625	1393	942	2584	759	508	558	593	856	3727

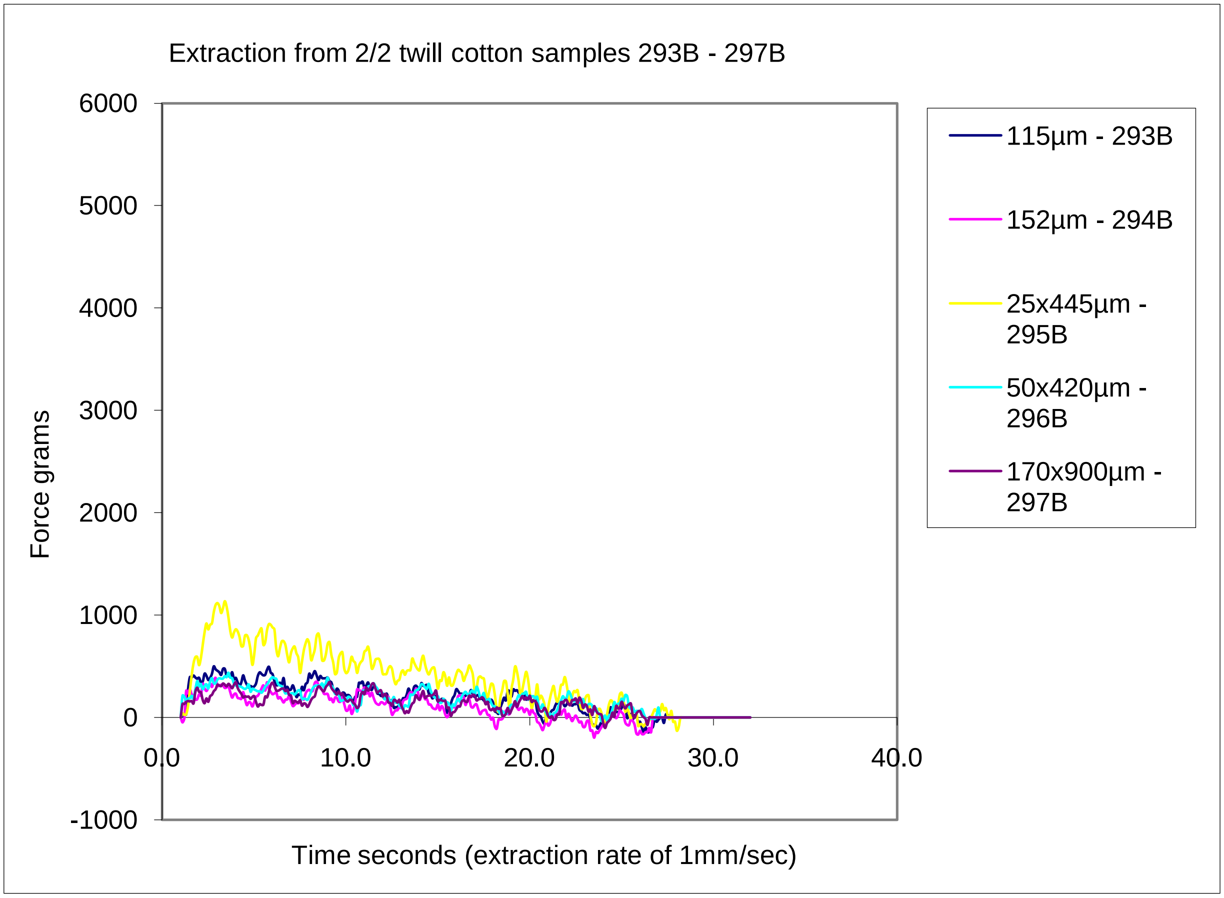
Sample no.	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623
Dimentions	50 x 30mm											100 x 30 mm					
Cotton Merc.	**Alternate Warp threads and every weft thread**																
Kevlar																	
Dacron																	
Duron Cl	**Alternate Warp threads**																
Plain weave	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2/2 Twill																	
plain & 2/2 Twill																	
63epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
81 epi																	
115µ Ø		x					x						x				
152µ Ø			x					x						x			
25x445µ				x					x						x		
50x420µ					x					x						x	
170 x900µ						x					x						x
Heavy Oxide							x	x	x	x	x						
Oxide			x	x	x	x								x	x	x	x
Oxide Free		x											x				
Fully Annealed		x	x	x	x								x	x	x	x	
Work hardened						x											x
Bend angle	47	37	36	40	40		37	36	54	40		47	37	36	54	40	
Load to first movement	873	483	64	287	415	283	527	96	1121	590	676		680	223	443	1035	598

Sample no.	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640
Dimentions	50 x 30mm											100 x 30 mm					
Cotton Merc.																	
Kevlar																	
Dacron																	
Duron Cl																	
Plain weave																	
2/2 Twill	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
plain & 2/2 Twill																	
63epi																	
81 epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x						x				
152µ Ø			x					x						x			
25x445µ				x					x						x		
50x420µ					x					x						x	
170 x900µ						x					x						x
Heavy Oxide							x	x	x	x	x						
Oxide			x	x	x	x								x	x	x	x
Oxide Free		x											x				
Fully Annealed		x	x	x	x								x	x	x	x	
Work hardened						x											x
Bend angle	38	33	34	37	35		33	34	37	35		38	33	34	37	35	
Load to first movement	885	514	264	432	719	956	627	291	503	405	727	665	861	406	408	408	1175

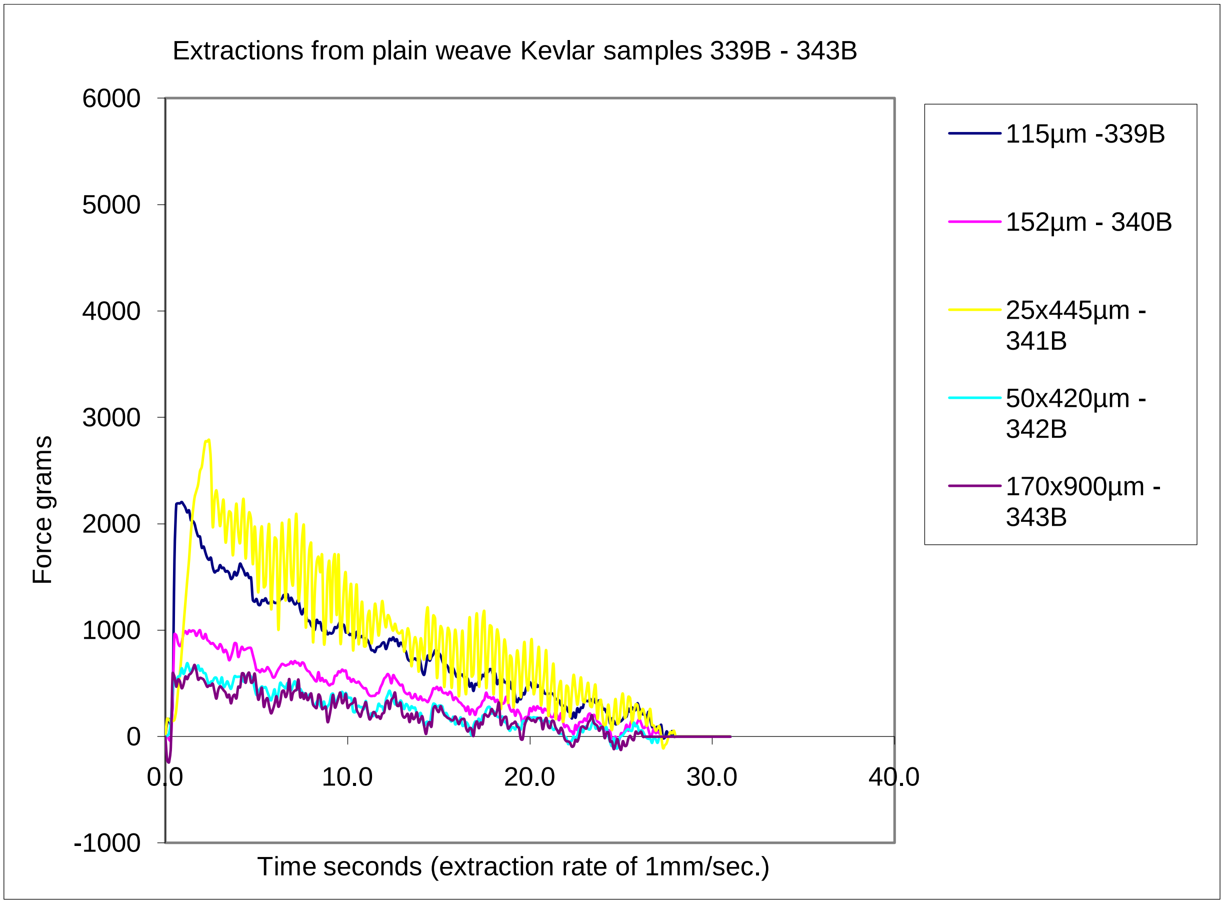
Sample no.	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657
Dimentions	50 x 30mm											100 x 30 mm					
Cotton Merc.																	
Kevlar																	
Dacron																	
Duron Cl																	
Plain weave																	
2/2 Twill																	
plain & 2/2 Twill	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
63epi																	
81 epi	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
115µ Ø		x					x						x				
152µ Ø			x					x						x			
25x445µ				x					x						x		
50x420µ					x					x						x	
170 x900µ						x					x						x
Heavy Oxide							x	x	x	x	x						
Oxide			x	x	x	x								x	x	x	x
Oxide Free		x											x				
Fully Annealed		x	x	x	x								x	x	x	x	
Work hardened						x											x
Bend angle	20	35	36	44	40		35	36	44	40		20	35	36	44	40	
Load to first movement	735	537	366	423	590	642	487	275	397	484	678	462	533	454	397	1174	1188

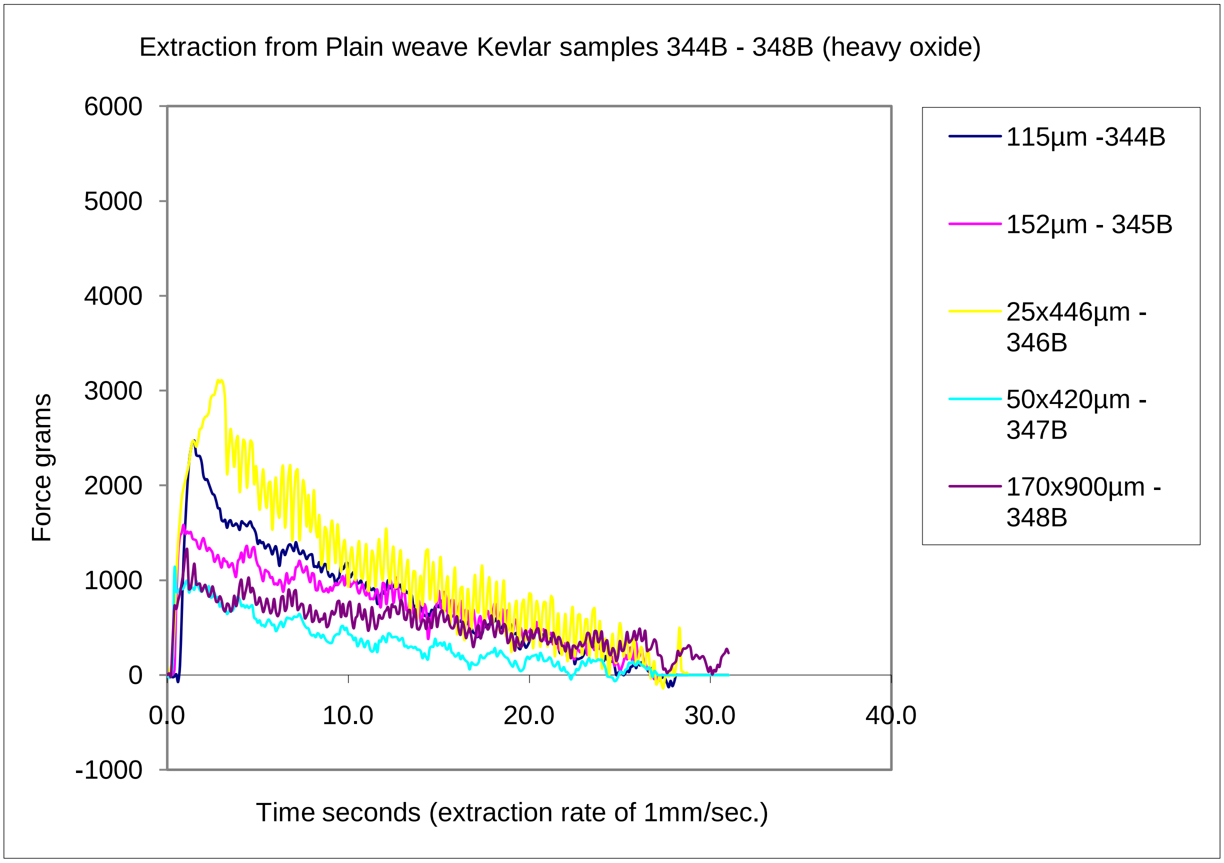
Appendix E. Dynamic friction results from the Instron tensile test machine. (originals in colour)



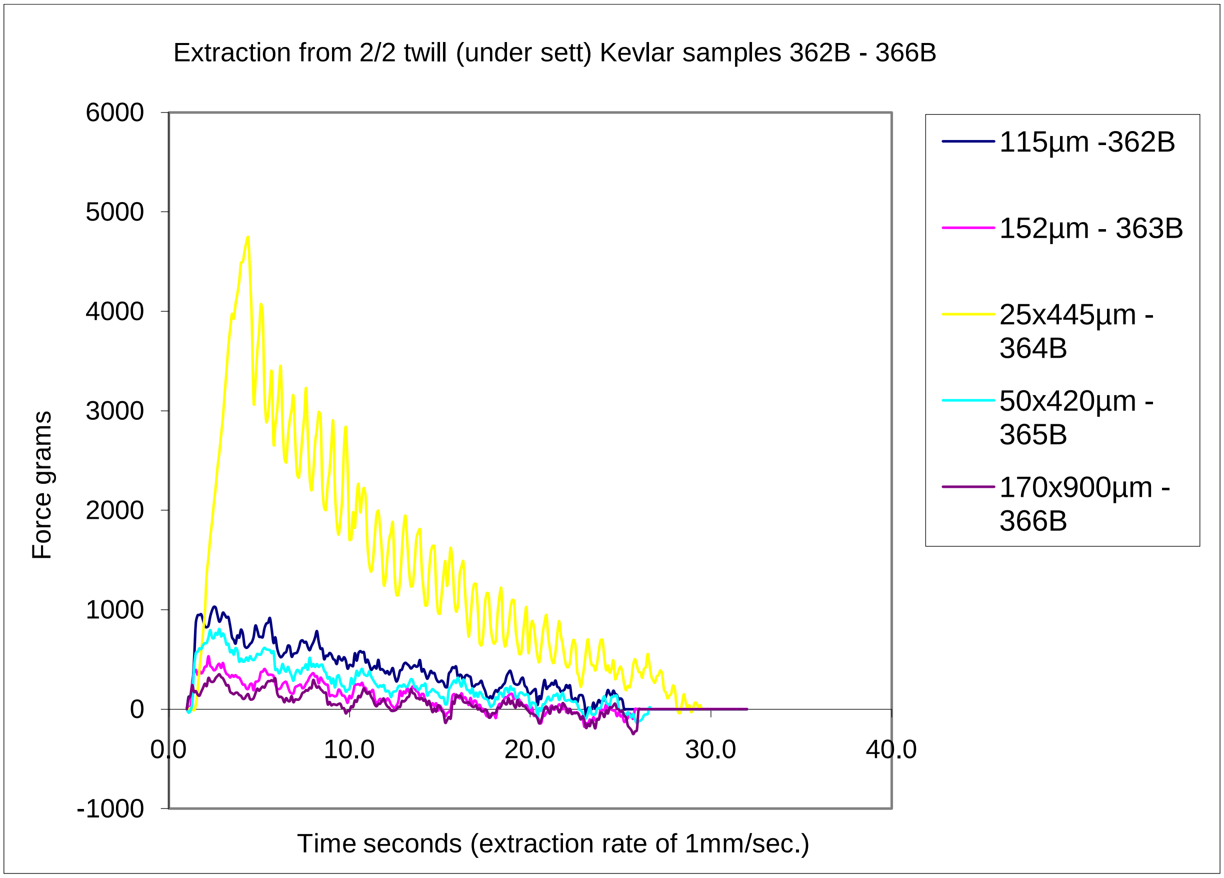


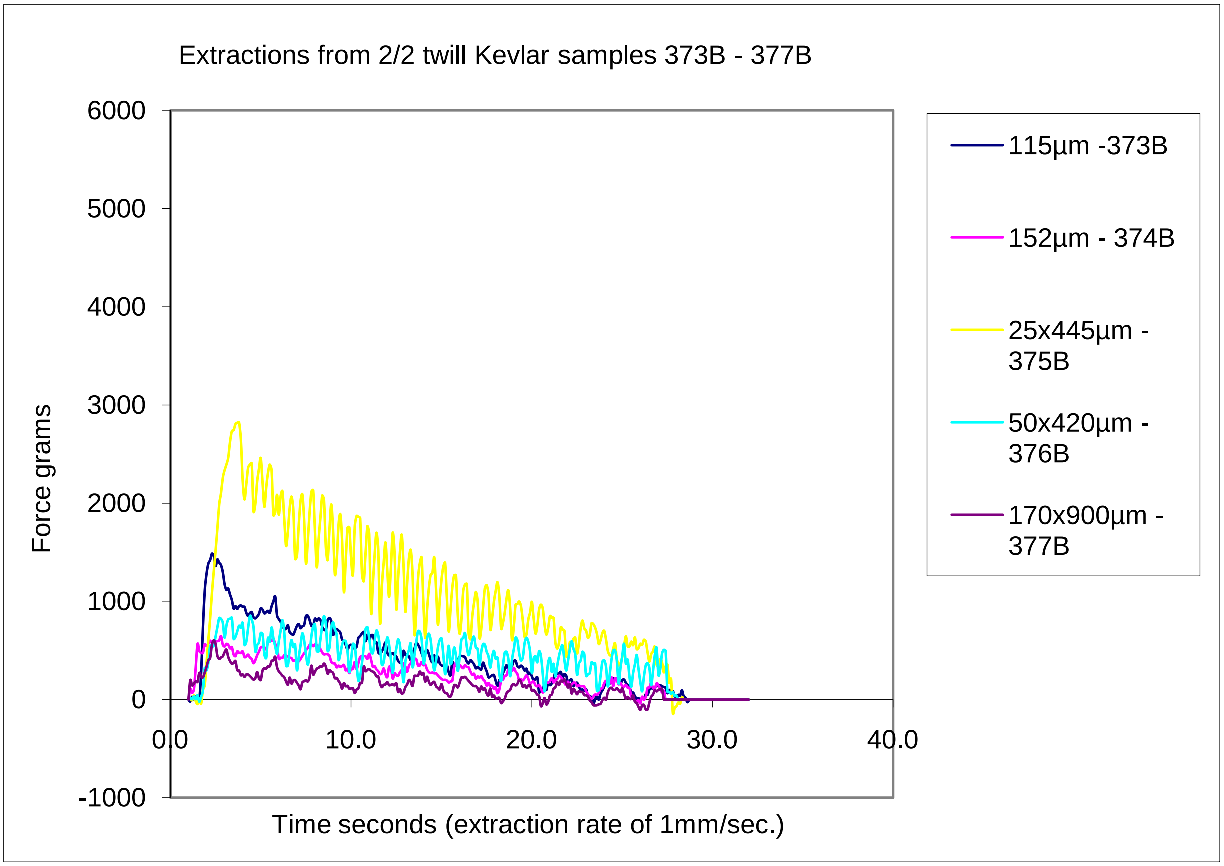
Appendix E. Dynamic friction results from the Instron tensile test machine. (originals in colour)



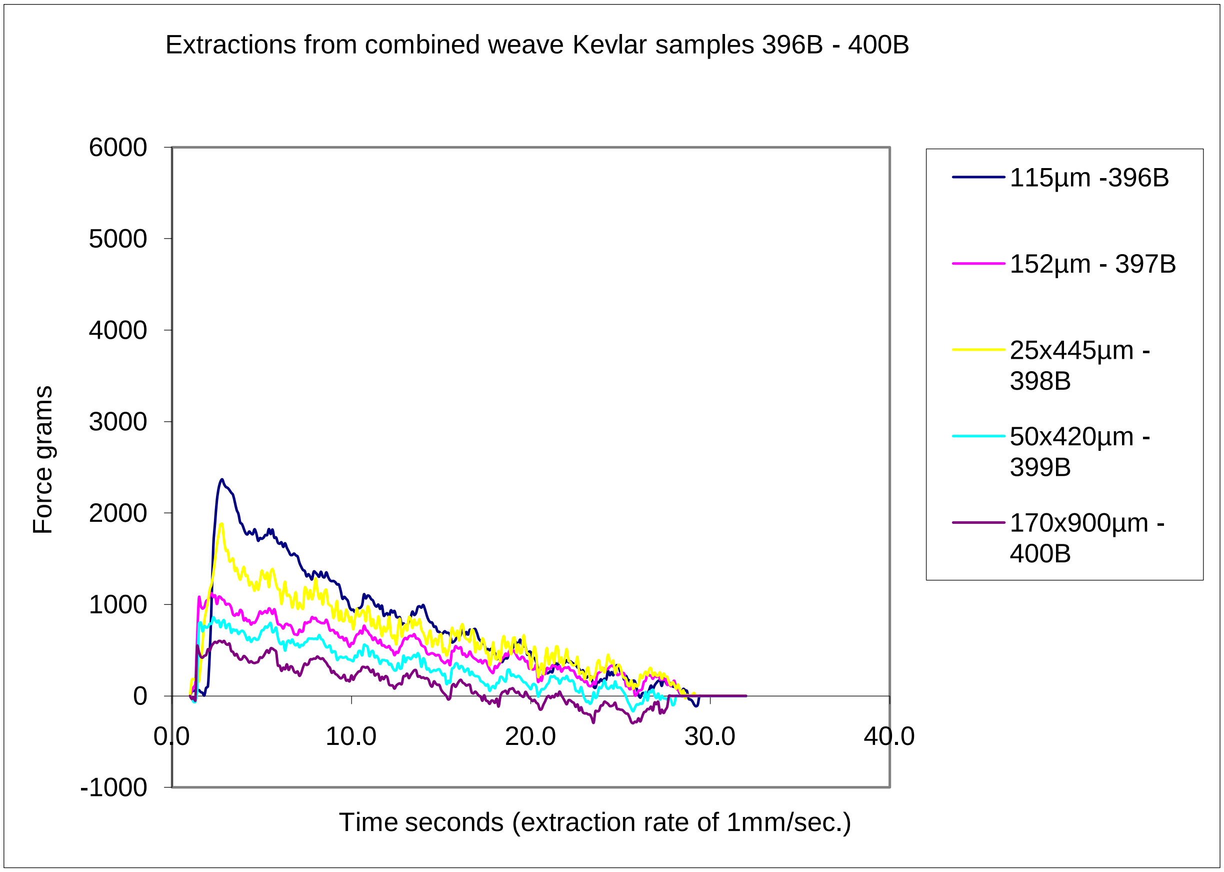


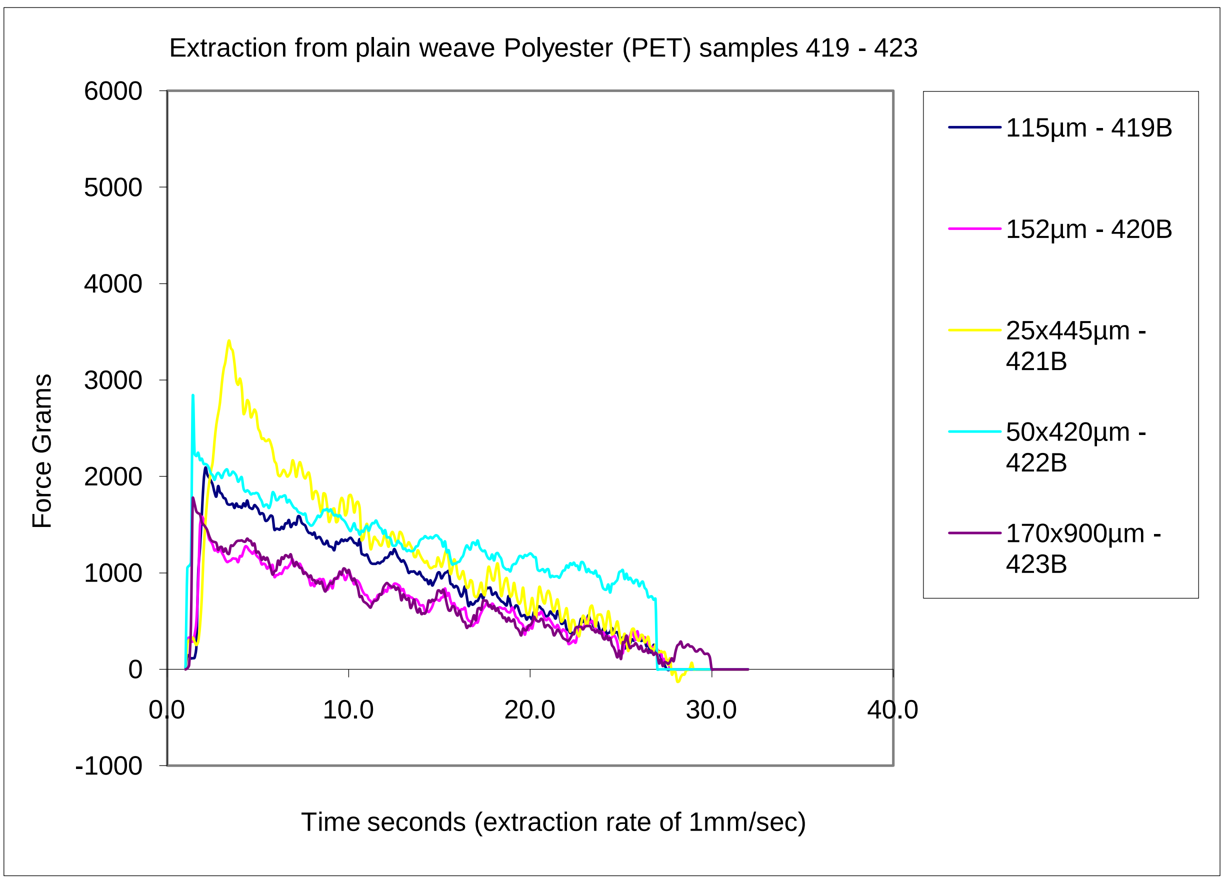
Appendix E. Dynamic friction results from the Instron tensile test machine. (originals in colour)



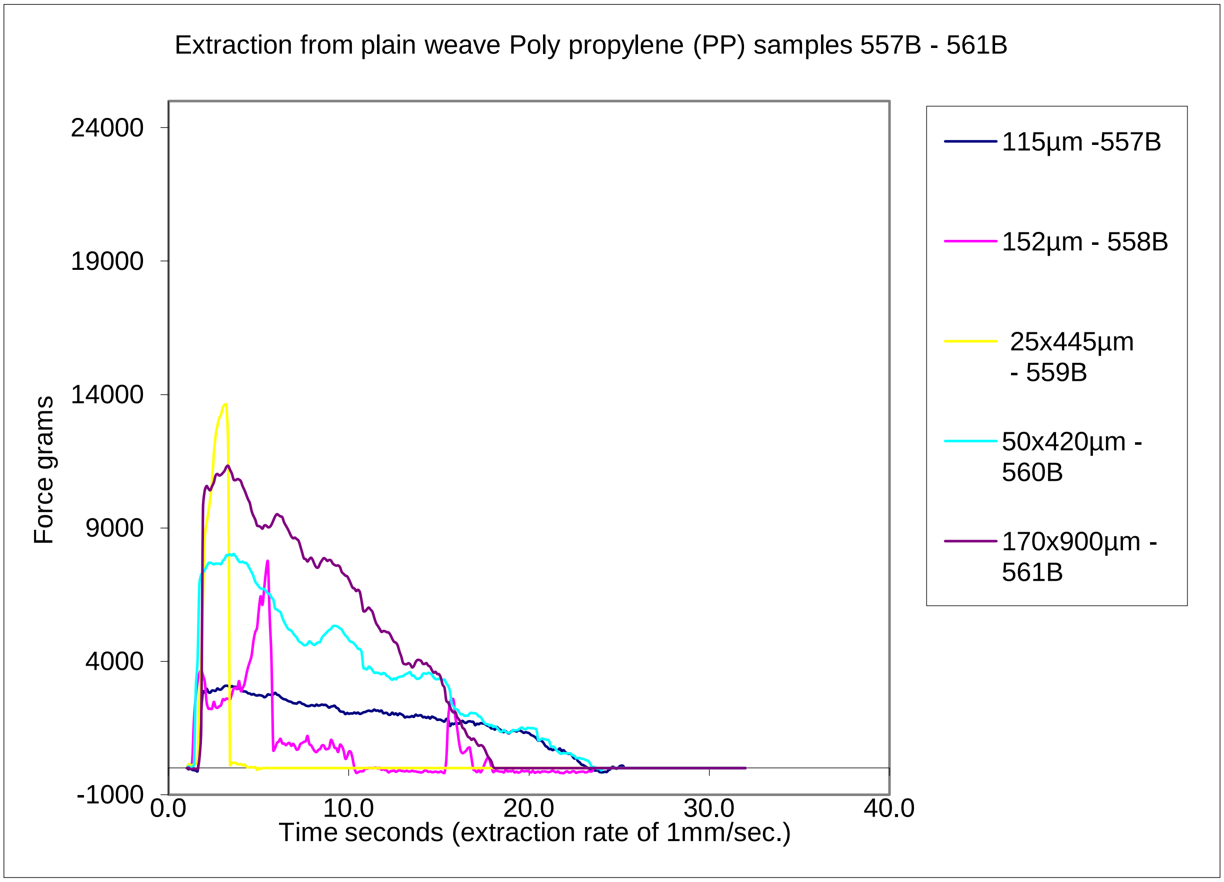


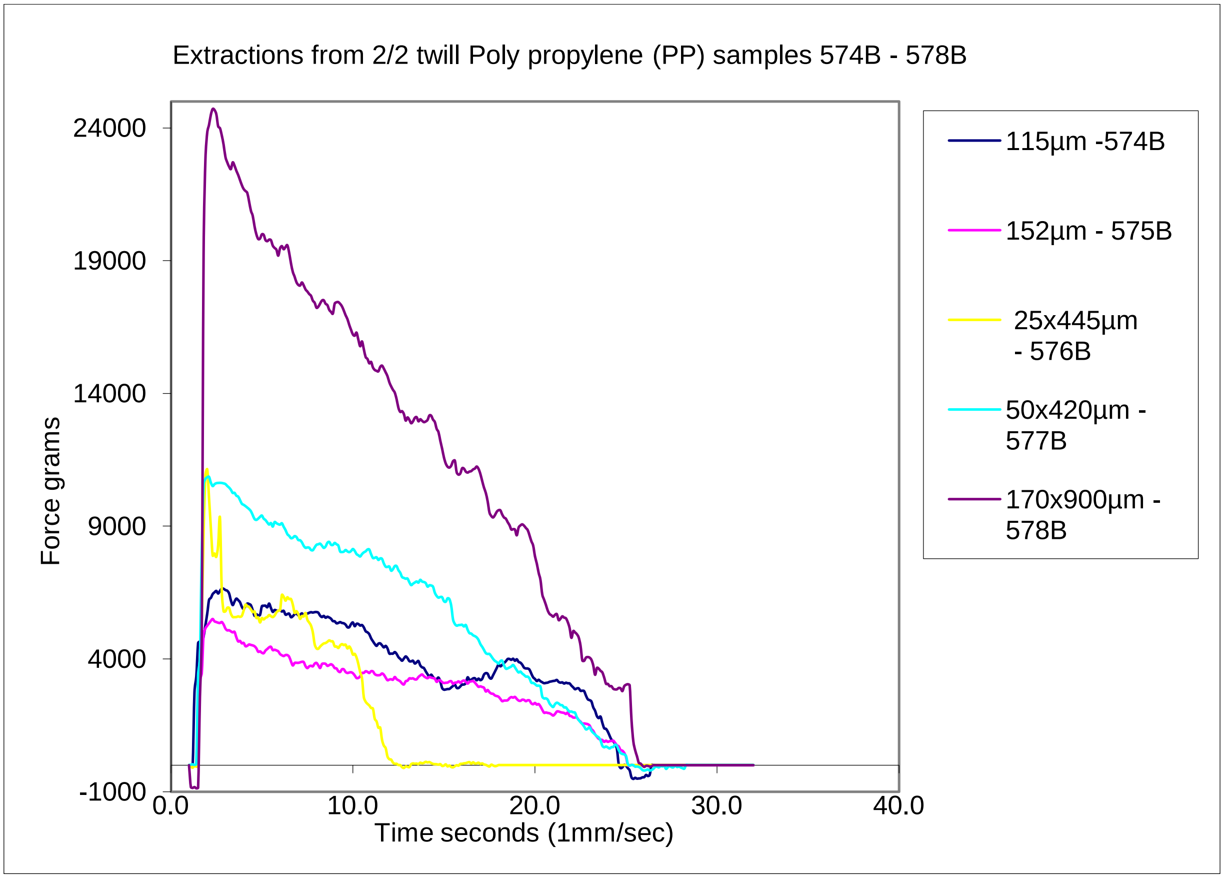
Appendix E. Dynamic friction results from the Instron tensile test machine. (originals in colour)



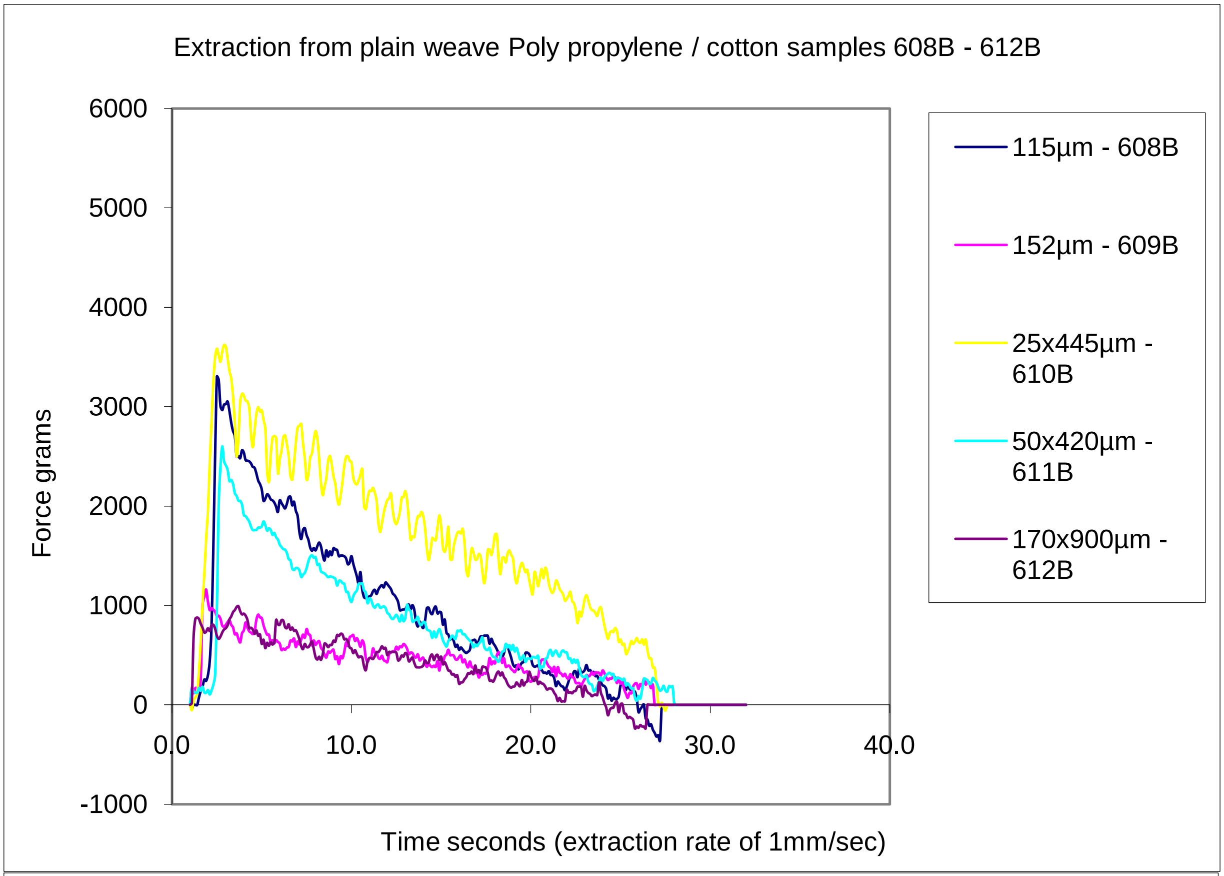


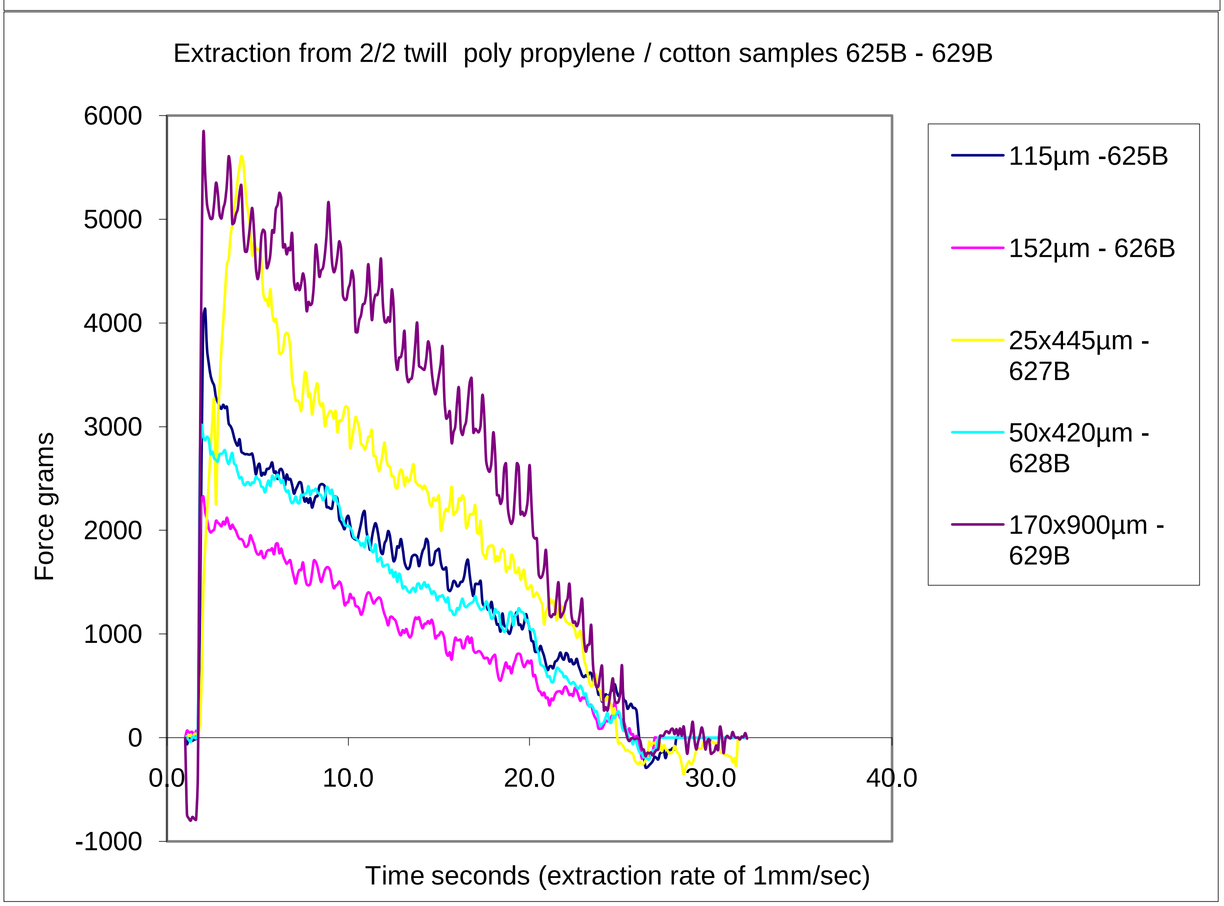
Appendix E. Dynamic friction results from the Instron tensile test machine. (originals in colour)





Appendix E. Dynamic friction results from the Instron tensile test machine. (originals in colour)





Appendix E. Dynamic friction results from the Instron tensile test machine. (originals in colour)