Programmable Materials (2024), **Vol. 2**:e5 1–18
doi:10.1017/pma.2024.5

PROGRAMMABLE MATERIALS

PERSPECTIVE

An introduction to linkage fabrics and their application as programmable materials

Mark Ransley[1,2], Christian Partik[1,2], Elze Porte[1,2], Anna Ploszajski[1], Richard Jackson[1], Ben Oldfrey[1,3], Danielle Purkiss[1,2], Martyna Michalska[1,4] and Mark Miodownik[1,2]

[1]Department of Mechanical Engineering, University College London, London, UK.
[2]Institute of Making, University College London, London, UK.
[3]Global Disability Innovation Hub, University College London, London, UK.
[4]Manufacturing Future Labs, University College London, London, UK.

Corresponding author: Mark Miodownik; Email: m.miodownik@ucl.ac.uk

Received: 10 March 2023; **Revised:** 11 December 2023; **Accepted:** 24 April 2024

Keywords: active; actuators; adaptive; animate materials; autonomous; programmable; self-repairing; sensors; smart; wearable

Abstract

Linkage fabrics are gaining in popularity and finding applications in architecture, aerospace, healthcare, and fashion because they can deliver materials with bespoke flexibility and strength through the geometric design of linkage nodes. In this article, we provide a perspective on linkage fabrics as a new class of programmable materials. We describe the theory and design principles of these linkage fabrics and show how they can be designed and simulated using digital tools, and fabricated using 3D printing. This digital approach overcomes a major obstacle to the adoption of these materials, namely their complexity. We show how simulation methods can be verified and calibrated through experimental testing. This perspective article also discusses design-led research challenges for linkage fabrics such as the development of wearable assistive devices for those with physical disabilities.

Introduction

Linkage fabrics are materials that can be defined as ‘an assembly of mechanical linkages that behave in aggregate as a fabric, with the ability to rotate freely at linkage nodes’ (Kock et al., 2013). A characteristic property of all linkage fabric materials is that the fabric’s flexibility arises from the interaction between the links and not from the elastic behaviour of the link material. Chainmail was the first linkage fabric, a highly priced technology since ancient times; it was revered globally to provide wearable protection in battle. Made from interconnected metal links, it had the flexibility of a textile and the hardness and toughness of steel. Originating from either the Celtic or Etruscan civilisations around 400 BC (Bishop and Coulston, 2006), the structure spread rapidly throughout the world remaining an invaluable asset on the battlefields of Europe until the sixteenth century, and well into the twentieth in Asia and the Middle East.

Historically, the most common type of chainmail pattern is the lorica hamata, or European 4-in-1 (E4-1), design (see Figure 1a) used en masse by the Roman Empire (Sim, 1997). In this design, each ring passes directly through four of its neighbours (hence the 4-1 designation), with a characteristic weave arising from the two opposing ring orientations. Linkages could be doubled up to increase strength, and the trade-off between weight and strength has long been a design feature with regional,

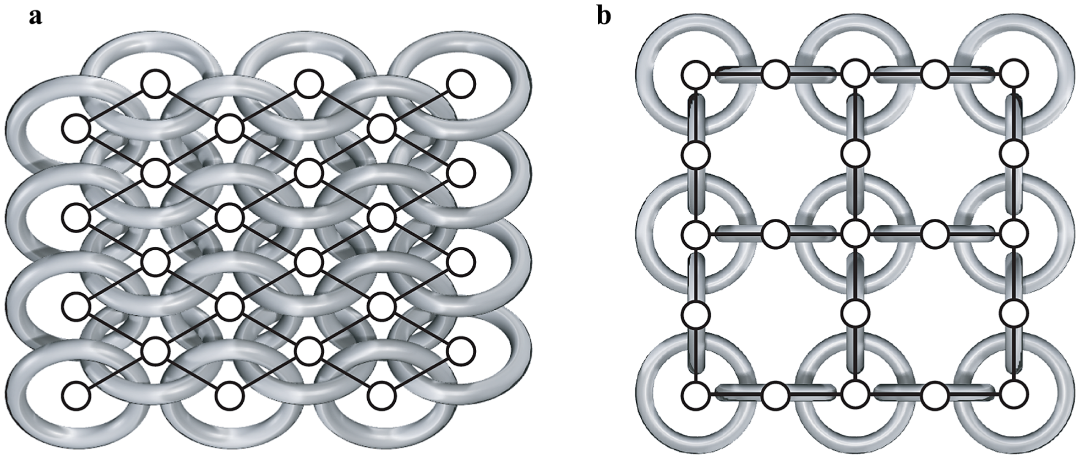

Figure 1. *(a) E4-1 and (b) J4-2 chainmail patterns with graph representation overlaid.*

historic, and anatomical variations controlled largely through the ring ratio of the inner to outer diameters (Kenkare, 2005).

Variations on the E4-1 style are limited, with the only substantially different patterns emerging from Japan. Chain armour or kusari has been dated back to thirteenth-century Japan and whilst the E4-1 style was still used heavily, the Japanese also offered 4-in-2 (J4-2) weaves (Figure 1b), where linkages tangential to the body are joined by orthogonally aligned connector rings (Bottomley and Hopson, 1993). Chainmail armour fell out of favour as swords became supplanted by ballistic warfare (Bishop and Coulston, 2006), though it is used as protective clothing to this day by butchers, fishmongers, and those expecting to swim with sharks.

There has been a resurgence of interest in recent times due to the advent of 3D printing, with its ability to manufacture complex structures from a variety of materials. The use of digital CAD tools to design the linkage fabric allows the geometry and degrees of freedom of each individual link to be specified. This is one of the features of linkage fabrics that makes them inherently programmable. It means that with minimal computational overhead, an almost infinite range of shapes and mechanical linkage mechanisms can be explored. This creates many new opportunities for creating linkage fabrics with bespoke properties for applications beyond traditional chainmail armour. For instance, high-profile fashion designers have showcased printable clothing concepts based on linkage fabrics (Flaherty, 2013) and NASA's Jet Propulsion Laboratory and the Californian Institute of Technology showcased a linkage fabric for spacecraft applications comprising unit cells of intersecting rings with square tiles on the outer surface, offering enhanced protection from radiation (Landau, 2017).

A range of methods are used to manufacture linkage fabrics. Electroplating techniques have been used to manufacture microscopic metal linkage fabrics with stretch-dependent conductivity where mechanical deformation resulted in a variation in resistance of nearly seven orders of magnitude (Ransley, 2023). In 2015, Rudykh et al. (2015) used a multi-material 3D printer to produce a linkage fabric which combined stiff tiles within a flexible gel matrix where the opposing properties of flexibility and stiffness could be controlled. They show that the flexibility of this structure could be programmed as a function of the dimensions and angle of the tiles.

In 2017, Ransley et al. (2017) suggested that linkage fabrics could be used for soft robotic applications due to their ability to modulate stiffness and flexibility. They showed that the mechanical properties of individual links in a fabric can be actively controlled using shape memory alloys. They noted that this requires a continuous power source, which is a drawback for wearable applications. Other research groups have shown that the fabric stiffness can be controlled using granular jamming, again requiring a power source (Wang et al., 2021; Hu et al., 2023; Tian et al., 2023; Xu et al., 2023).

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

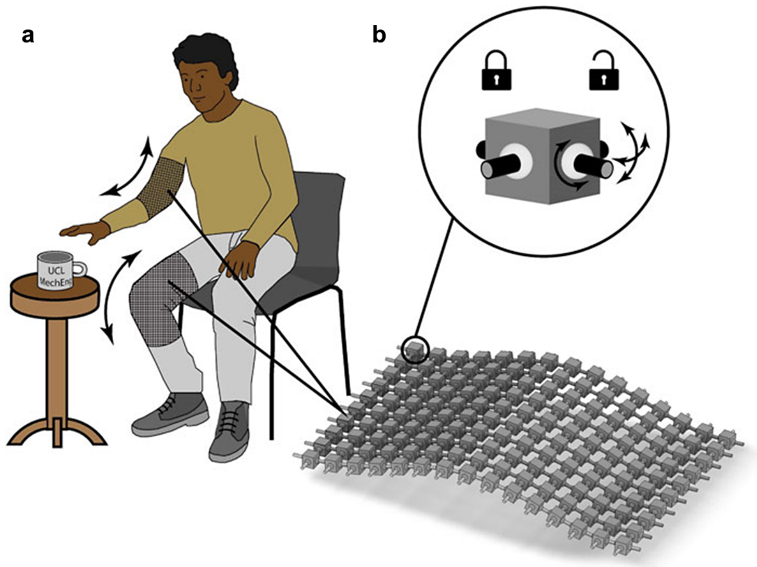

Figure 2. Schematic of wearable assistive linkage fabric: (a) a demonstration of how wearable assistive devices can actively modulate stiffness on demand is envisioned to support joints and facilitate limb movement; (b) showing the details of the linkage fabric consisting of block-shaped links that are connected through flexible joints that can be locked and unlocked on demand (Partik et al., 2023).

Recently, Ploszajski et al. (2019) explored the application of active linkage fabric materials to aid the limb movement and mobility of those with disabilities. In these scenarios, the fabrics actively support weak muscles and are worn as garments. For these applications, since each person is a different shape and size, they require assistive technology that exactly fits them. This is where 3D printing technology unlocks the potential of linkage fabrics because they can be made bespoke for individuals through digital design and additive manufacturing. Partik et al. (2023) envisage a future where linkage fabrics are printed to order and worn by individuals who need assistance with movement as depicted in Figure 2.

In this article, we introduce the fundamentals of linkage fabrics. The article is structured to first introduce the theory and simulation of these structures, as well as experimental validation of these frameworks. We then consider the design of passive linkage fabrics and explore the parameters that make them programmable materials. We then move on to introduce active linkage fabrics which involve the use of actuators to achieve the properties required to produce wearable assistive technology depicted in Figure 2. Finally, we discuss the barriers and technological hurdles that must be overcome to obtain the full potential of linkage fabrics, including sustainability.

Theory and simulation of linkage fabrics

Graph representation

A linkage fabric is a network of connected parts, so it can be described by a network graph where each node represents the centroid of a linkage and an edge joining two nodes represents their linkages being interlinked. Figure 3 shows this network graph for a J6-2 chainmail structure. The graph representation allows us to describe the structural differences between E4-1 and J4-2 chainmail styles. Conversely, two fabrics could appear visually very different but be isomorphic by sharing a common topology. Understanding linkage fabric topology is important because all shape changes in the fabric must preserve topology. Network graphs are a fundamental data structure with a wealth of well-defined properties and algorithms for their traversal, revision, analysis, and optimisation at scale. The graph

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

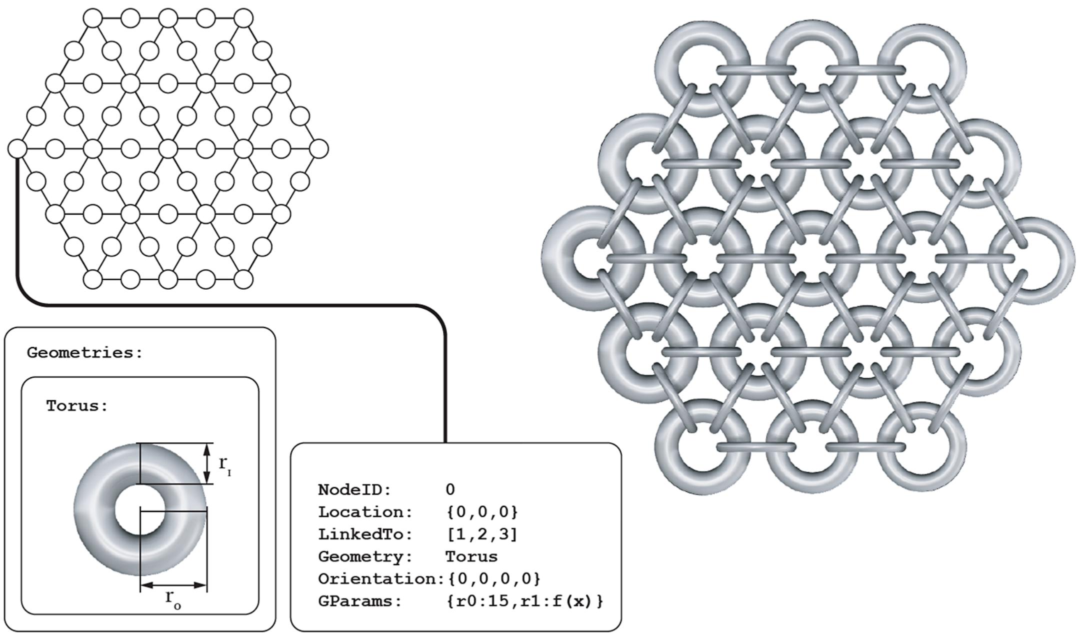

Figure 3. *A graph and a set of parametric geometry templates define a parametric linkage fabric, here based on the traditional J6-2 chainmail. For each in-plane node, the* r_1 *parameter is proportional to its distance from the origin.*

representation thus provides a sound basis for the construction, categorisation, and study of novel linkage fabrics. Furthermore, it becomes essential to use graphs when dealing with more complex architectures that lack a regular grid topology since standard spatial iterators are unsuitable for their traversal. This formulism also provides a measure to evaluate the graph's topological invariance during numerical simulations of kinematics to determine whether active transformations of the links have been completed successfully.

Figure 3 illustrates a torus linkage fabric, which can be given a node class to contain the input parameters. This approach allows the individual geometry of each link to be varied throughout the specimen while maintaining the graph formulism (Ransley, 2023). This provides a convenient approach to implement to simulate the global changes in the linkage fabric as well as its mechanical properties such as flexibility and stiffness.

As shown in Figure 3, a simple ring torus may be parameterised by two variables r_0 & r_1, which can be combined to yield a dimensionless quantity known as the ring ratio $r_r = r_0/r_1$. A chainmail with uniform r_r across all links becomes less compliant as r_r *tends to* 1. A simple geometric analysis (Ransley, 2023) yields the condition that $r_r \geq (3+\sqrt{2})/2$ for a ring to accommodate its four neighbours in a J4-2 fabric. For the orthogonally aligned rings that only accommodate their two neighbouring linkages, this requirement is relaxed to $r_r \geq 2$. At the limits of these conditions, the linkages are able to rotate (ignoring friction) but not translate in respect to their neighbours making the fabric fully constrained. As we will see later linkage fabrics are not limited to the use of toroidal linkages, and yet despite the great difference in physical appearance of different linkage fabrics, the graph representation remains applicable. This is because all changes in shape of a linkage fabric must preserve the linkage fabric's network topology graph (Ransley, 2023).

Simulating linkage fabrics

The modelling and simulation of traditional fabrics has been an established field since the 1980s and currently finds significant application across numerous industries including the film and gaming

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

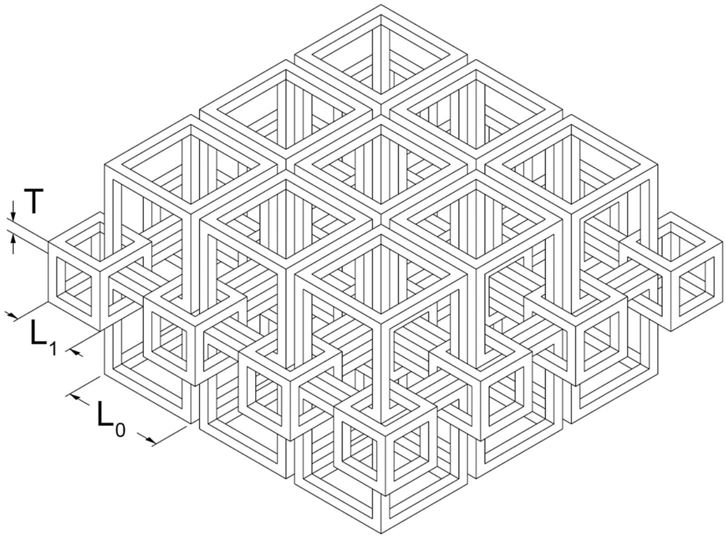

Figure 4. *The Cubic Linage Fabric used in the Digital Drapemeter Test, with parametric flexibility profile determined by L_0, L_1, and T.*

(Kavan et al., 2011), high-performance textile engineering (Jiang et al., 2019), architecture (Nabaei et al., 2015), and e-commerce (Meng et al., 2010). We use rigid-body physics engines (Bullet Real-Time Physics Simulation, n.d.; NVIDIA PhysX System Software, n.d.; Project Chrono, n.d.) to design and simulate the behaviour of linkage fabrics in this article. To do this, the linkage fabrics are assumed to be multi-body systems – or articulated rigid bodies – which are defined as sets of objects where each is connected to at least one other via a mechanical joint. Methods such as Featherstone's Algorithm (Featherstone, 2016) exist for determining the behaviour of a multi-body system given the reduced configuration space. In the case of the linkage fabrics, the individual links remain rigid at all times. The role of the model is to accurately simulate how these rigid bodies interact with each other while maintaining the topology. Thus, the bodies need to intersect one another where the topology allows but not in prohibited ways such as where two volumes occupy the same space. In this context, it is important to maintain a distinction between the contact between solids, which all rigid-body engines are capable of detecting and resolving, and the interlinking of elements in a linkage fabric, where solids do not actually intersect. We use graph theory (Ransley, 2023) to determine whether two linkages are topologically interlinked and detect violations of this with the simulations.

Many open-source physics engines that are capable of performing these simulations exist. The efficiency and suitability of three 3D physics engines – Bullet (Bullet Real-Time Physics Simulation, n.d.), PhysX (NVIDIA PhysX System Software, n.d.) and Chrono (Project Chrono, n.d.) – have been compared for simulating linkage fabric kinematics. To validate their accuracy, their ability to simulate a simple linkage fabric has been compared to the results from experimental data of a physical fabric. The topology preservation test (computed from the network topology graph) was implemented using the existing capabilities of the three physics engines, which each provide methods for checking the penetration depth of any two collision shapes. The cubic linkage fabric was used in these simulations, as shown in Figure 4. All simulations were run on a custom-built PC (Processor AMD Threadripper 1900X 3.8, GHz 8-Core RAM 32GB DDR4 2400, GPU Nvidia GeForce GTX1080 8GB, OS Windows 10 Professional) (Ransley, 2023).

Simulation validation

Characterising the three-dimensional deformation is key to validating the rigid-body simulation to physical samples. We conduct a series of drape tests, comparing the measured drape of simulated

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

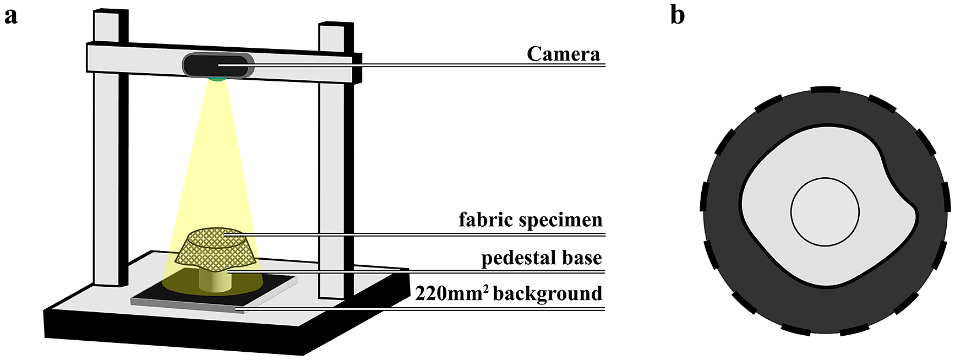

Figure 5. *Cusick-style Drapemeter used for measuring drape of the linkage fabrics: (a) the drape meter setup using a 3D-printer frame and a Logitech Brio 4K camera, (b) the silhouette of the fabric as recorded by the camera.*

and physical fabrics, via the Cusick method (Cusick, 1968). Therefore, Cubic Linkage Fabrics (CLF) (Figure 4) were designed and 3D-printed using an EOS P100 Formiga SLS machine using PA 2200 (nylon powder), with design parameters set to $T = 1$ mm, $L_0 = 6$mm, $L_1 = \{6, 5.8, 5.6, 5.4, 5.2, 5.0\}$ mm, fabric radius $r = 90$ mm according to Figure 4.

The flexibility of the fabrics was measured in simulation and real life using a drape meter setup (Figure 5), in which the specimen was placed centrally on a circular pedestal with $r = 53.5$ mm, $h = 80$ mm that in turn was mounted on a matte black platform. Above it, a Logitech Brio 4K Professional webcam was mounted on a frame to allow for a precise alignment and recording of the fabric silhouette, as shown in Figure 5a.

The Cusick method evaluates a fabric's Drape Coefficient (DC) (Ransley, 2023) as the ratio of the areas cast by its silhouettes in the flat versus draped states, given by Equation (1):

$$DC = \frac{Area_{draped} - Area_{pedestal}}{Area_{flat} - Area_{pedestal}}. \tag{1}$$

To photograph the fabric atop the pedestal in its flat state, an additional matte black platform was temporarily inserted between the fabric and the pedestal (Figure 6a). This was then removed to photograph the fabric in its draped state (Figure 6b). An additional image was taken of the pedestal alone (Figure 6c) to compute DC using an image processing routine.

For the simulation, the CLF specimens with equal dimensions compared to the printed samples were centred on a cylinder with $r = 53.5$ mm, $h = 80$ mm, with a 235×235 mm plane at the base. Rigid-body simulation was then advanced through time to equilibrium, with data passed to the render engine at each frame and renders being saved for computation of DC in post-processing (Figure 7). The custom rendering engine was programmed to place the camera 30 cm above the base pointing downward with 90° field of view to match the experimental setup.

The images featuring the fabric specimen were then processed using a floodfill algorithm from OpenCV, yielding the binary masks as shown in Figure 6d–f. For the pedestal image, where the contrast was lower, the mask was created manually by adjusting a circular mask's radius and midpoint until a fit was achieved, again with OpenCV. Masks were then inverted and each image's pixels summed to measure the areas of each silhouette, in pixels.

For each 3D-printed CLF, the Cusick Drape Test was carried out four times (twice on each side). The standard deviations of the computed Drape Coefficients for each fabric, in contrast to the change of L_1, were found to be 0.27%, 0.37%, 0.53%, 0.63%, 0.30%, and 0.96%, indicating that the Cusick Drape Test is highly repeatable and thus well suited for characterising linkage fabrics (Ransley, 2023).

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

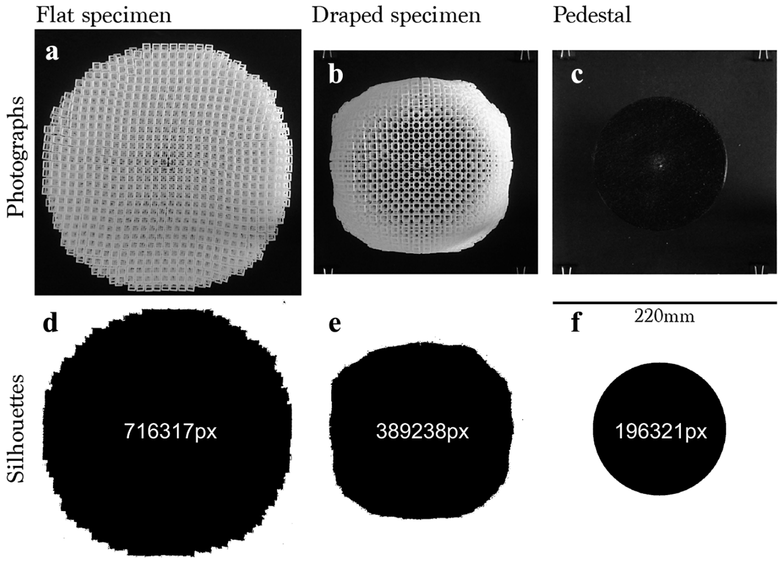

Figure 6. *Physical drapemeter camera output (a–c) and image processing steps (d–f).*

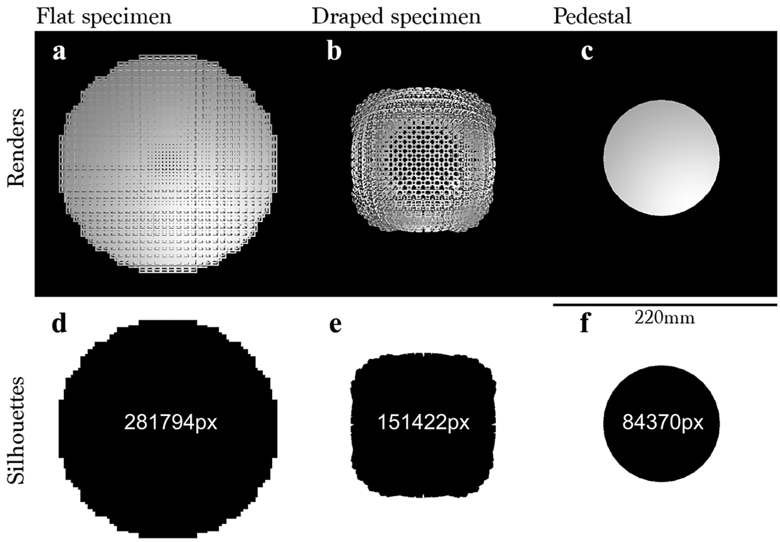

Figure 7. *Virtual drapemeter render output (a–c) and image processing steps (d–f).*

Simulation of the linkage fabrics was carried out on a virtual pedestal (see Figure 7a–f). Comparing physical and simulated sample results was found to accurately (within standard deviation) match the physical measurements for $L_1 = 6.0$. However, for smaller values of L_1, the simulated DC significantly deviated (up to 18%) for all three physical engines (Ransley, 2023). To understand where the error was coming from, the actual size of the individual links of the 3D-printed fabrics was measured and a discrepancy was found between the designed thickness and the actual thickness after 3D printing. This experimental error arises because 3D printing is a highly variable process between batches, even in high-quality machines such as the EOS P100 Formiga SLS machine we used. When the simulation results were adjusted compensating for the measured link thickness, there was good agreement between the simulation and experiment. The normalised sum-square of errors for Chrono, PhysX and Bullet were found to be 2.29%, 3.85%, and 13.22%, respectively (Ransley, 2023). As such, it can be said that the

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

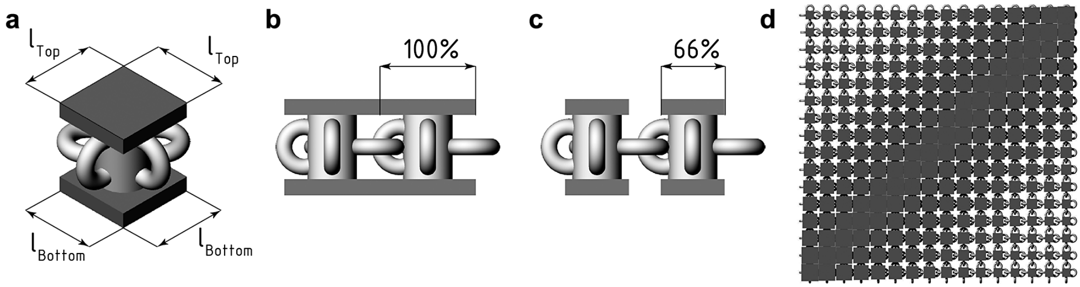

Figure 8. *Design and simulation of a spatially inhomogeneous linkage fabric with graded flexibility. Design parameter l varies between* 66% → 100% *of the unit cell length scale according to distance from the fabric's diagonal line; (a) individual link, (b) showing interlinking of the fabric at* 100% *of the unit cell, (c) showing interlinking of the fabric* 66% *of the unit cell, (d) overview of whole fabric.*

presented simulation tools can predict the three-dimensional behaviour of linkage fabrics to reasonable levels of accuracy.

Programming the mechanical properties of linkage fabrics

There are two basic categories of linkage fabrics, passive fabrics, and active fabrics. The former are defined by their design, with the possibility of a range or a gradient of properties across the fabric through the manipulation of the geometry of the individual links and their topology. They are passive in the sense that neither the individual links nor the fabric itself can actively change shape. This is in contrast to active linkage fabrics, which can do this.

Passive linkage fabrics

Simulation platforms are typically used to design passive linkage fabrics with a range of mechanical properties. For instance, Figure 8 demonstrates a link design which features a square tile on top and bottom connected by a column through the middle on which four toroidal loops provide the connection to neighbouring links. There is one variable parameter in this link design, $l(l_{Top} = l_{Bottom})$, the size of the square tiles. If l is constant throughout the fabric and equals the unit cell distance, then the fabric is fully stiff and has zero flexibility. However, by functionally grading the l across the fabric, in this case between 66% → 100% (see Figure 8b,c) of the unit cell length scale according to distance from the fabric's diagonal line, a very different result is obtained (Figure 8d).

The resulting linkage fabric is completely rigid along the diagonal, becoming increasingly flexible as the distance from the diagonal increases. A prototype of the 15 × 15 element textile (see Figure 9), was manufactured using an EOS Formiga P100 SLS printer with PA 2200 nylon powder and was suspended from both sides to showcase the degrees of flexibilty along the fabric, while compensating for the printer limits on minimal distance between link elements which was 0.2 mm.

Figure 10 shows the behaviour of the same fabric, but this time where l_{top} and l_{bottom} of the square tiles are independent variables but remain constant across the fabric. By setting l_{bottom} equal to the unit cell size, and l_{top} to 100% of the unit size, the fabric's flexibility becomes anisotropic. It was fully rigid to the extent that it was completely flat when placed on a beaker (Figure 10a,b), yet when flipped over was flexible enough to permit a doubly curved drape over the beaker (Figure 10c,d). These simple examples show the potential of passive linkage fabrics as programmable materials.

Active linkage fabrics

The successful control of fabric flexibility through the control of linkage parameters, as shown qualitatively in Figure 10, opens the possibility of dynamically controlling the fabric. Figure 11a shows

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

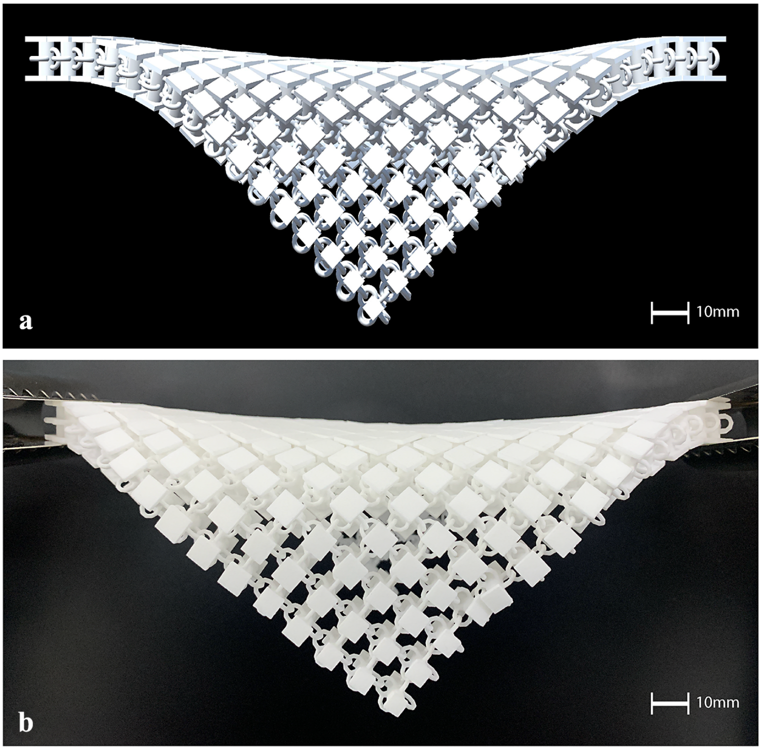

Figure 9. (a) Simulation and (b) 3D print of a spatially inhomogeneous linkage fabric with graded flexibility suspended from their corners. The simulation shows good qualitative agreement with the experiment.

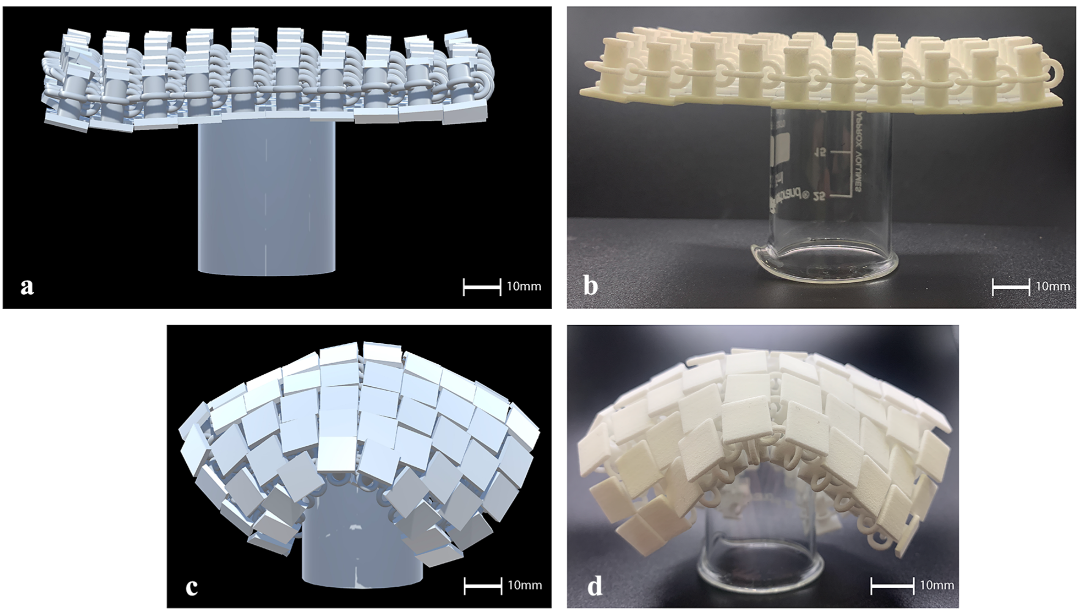

Figure 10. (a) Simulation and (b) 3D print of a spatially inhomogeneous linkage fabric with graded flexibility placed on a beaker (c,d). The simulation shows good qualitative agreement with experiment.

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

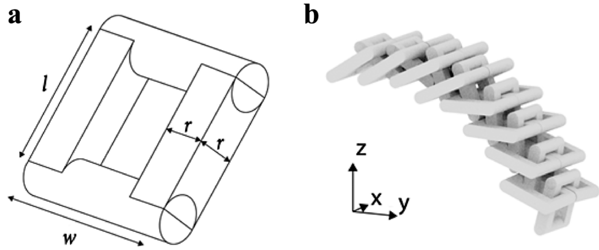

Figure 11. *(a) A single link design showing geometric variables, (b)* 8×2 *linkage fabric reaching drape equilibrium via the rigid-body framework, with reference coordinate frame (Ransley et al., 2017).*

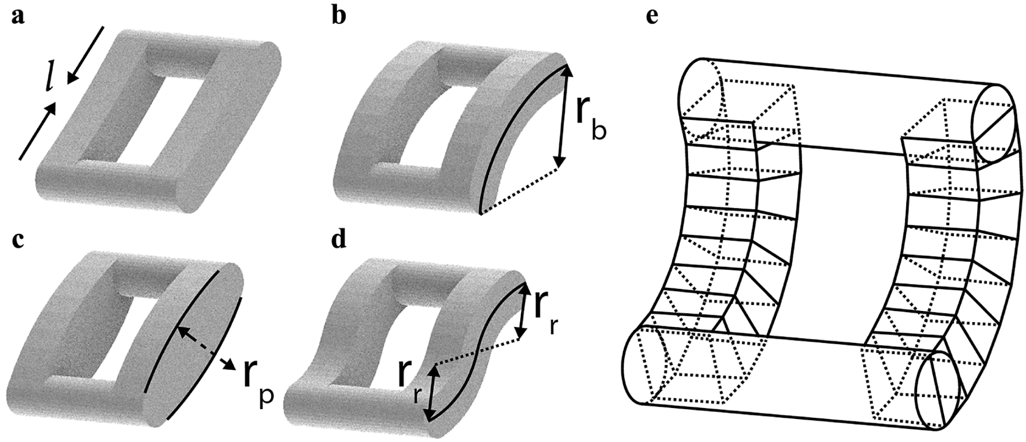

Figure 12. *Four mechanisms of actuator driven linkage deformation, here named (a) linear, (b) bimorph, (c) Poisson-expansion, and (d) recurve. A deformed linkage, shown here through the bimorph mode (e), can be constructed from a set of convex solids, with the curved elements being approximated by trapezoids, for use in rigid-body physics engines*

the design of a simple fabric link, which when assembled into a fabric creates a characteristic drape (see Figure 11b). When the links are passive, the fabric has a drape coefficient which is a function of the linkage parameters, l, r, and w (Figure 11). When these links become active, they can autonomously change their shape to create a global change in the fabric's drape.

Figure 12 shows different ways in which the linkage geometry can actively change such as a simple linear expansion (Figure 12a), a bimorph (Figure 12b), a Poisson expansion (Figure 12c), and recurve (Figure 12d). Figure 13 shows the dynamic behaviour of a 6×2 fabric made from these active linear expanding links. As the length l of the links was increased from $l = 3.0$ to $l = 3.3$ in the simulation, the global drape of the fabric actively changed as measured by κ_{max}. Simulated changes to the fabric drape that bimorph, Poisson-expansion, and recurve links showed that fabric flexibility can be actively controlled in all these different ways (Ransley, 2023).

Ransley et al. (2017) investigated the use of actuators in an experimental setting to actively manipulate the geometry of a linkage fabric. Figure 14 shows the experimental prototype of a 6×2 active linkage fabric. NiTi SMA coils were selected for actuators owing to their availability, high linear strain, and sensitivity to electronic actuation via Joule heating. Both arms of the linkage contained a paired spring system comprising a tensile NiTi coil nested within a compressive coil of regular spring steel (Figure 14a). The NiTi coils had to be pre-strained for good performance, and so were stretched along the length of the arms and secured in place via steel pins at each end of the linkage chassis, while the compressive coils were secured via cylindrical recesses in the linear coupling. The pins at

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

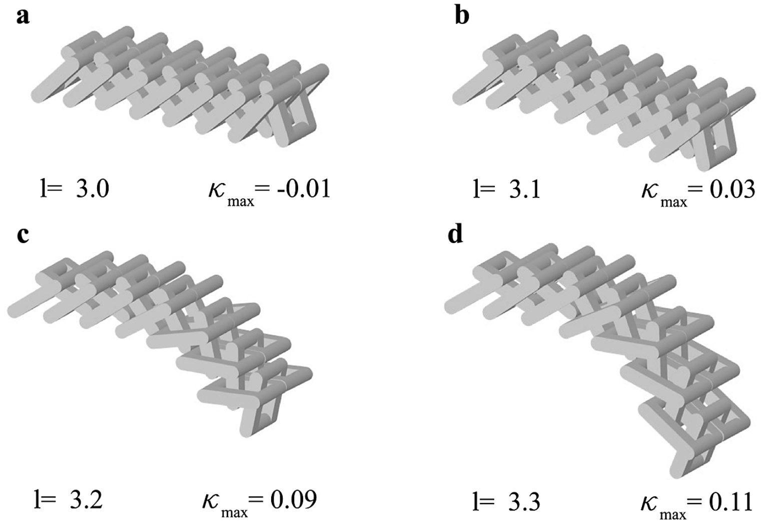

Figure 13. *Linear mechanisms of actuator driven linkage deformation for length steps (a)-(d) $l = 3cm$ to $l = 3.3cm$ (length l as shown in Figure 12a) with the maximal curvature value k_{max}.*

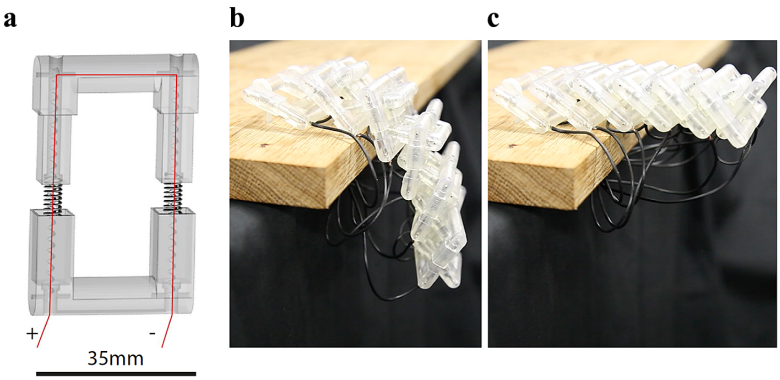

Figure 14. *Physical prototype of the active fabric, (a) design schematic (path of current highlighted in red), (b) draping from a surface at 0 V, (c) fully rigid at 24 V (Ransley et al., 2017).*

the top end were sufficiently long as to connect in the centre, forming the circuit highlighted in red in Figure 14a and allowing for the NiTi spring constant (and thus the linkage parameter l) to be physically modulated via Joule heating. Recesses were calibrated, so $l = 3.3$ cm in the cooled state and $l = 3.0$ cm when heated, corresponding to a 10% strain in the actuators and providing a geometric transformation that the preliminary simulations indicated sufficient to shift the fabric between flexible and rigid states. The linkage chassis were fabricated using a Formlabs Form 2 SLA machine in clear resin, while the NiTi archwire was obtained from orthodontics supplier Azdent Dental Corporation (AZDENT Dental Open Coil Springs Niti, n.d.). A 2×6 mesh was assembled and connected to a 24 V power supply, with the three linkages comprising each row connected in serial. Each linkage was weighed to have a mass of 8 g, which is used as a parameter in the simulation.

An experiment was conducted on the physical prototype whereby the fabric was tethered to a workbench by the lower cylinders of the first two linkages, with the remainder allowed to cantilever over the edge. Initially, at 0 V, the untethered linkages flexed downwards under the influence of gravity (Figure 14b). A potential of 16 V was then applied causing the NiTi springs to contract from $l = 3.3$ mm $\rightarrow$ 3 mm and the fabric to stiffen into a planar configuration (Figure 14c) which was maintained for 12.5 s after which the power was cut, allowing the NiTi springs to cool and regain their elasticity. The compressive springs then extended the linkages back to their initial length of l = 3.3 mm allowing the fabric to once again flex under gravity.

The physical prototype was observed to function as intended, serving as a compliant linkage fabric draping freely under gravity which then became completely rigid on the application of a voltage (Ransley et al., 2017). However, the hysteresis of SMA actuators was identified as a barrier to their applicability in the kind of wearable assistive technology depicted in Figure 2. Such technology needs to have fast-acting reversibility to match the responsiveness of muscles to meet human needs.

Magnetic actuation has also been used to create active linkage fabrics. Magnetic nanoparticles were embedded in the 3D-printed linkage fabric (Ploszajski et al., 2019). The method involves taking advantage of the porosity of laser sintered 3D-printed linkage fabrics and using capillary forces to suck ferrofluid into the structure, followed by drying under heat. This created a ferro-magnetic linkage fabric which was successfully actuated using magnetic fields (Ploszajski et al., 2019). The drawback of this actuating mechanism for wearable assistive applications is the requirement of a high magnetic field strength and the difficulty of implementing this into wearable technology. We discuss this issue in the next section.

Discussion and future directions

The research field of linkage fabrics is at an early stage. They are an unusual class of material whose stiffness and flexibility can be either passively or actively controlled. These attributes lend themselves to various engineering applications in the field of programmable materials. The areas that are receiving the most attention are reconfigurable orthoses (Ransley et al., 2017) and wearable assistive devices (Nguyen and Zhang, 2020; Partik et al., 2023). These materials present the opportunity to design and 3D print bespoke fabrics for patients to help with recovery from injury or to support weak muscles and damaged ligaments. For instance, a person with a wrist or shoulder injury need not have all movement restricted by a traditional cast, which is uncomfortable and leads to muscle atrophy and muscle shrinkage. Instead, a linkage fabric could be designed to prevent movement that aggravates the injury but allows flexibility for other motion as depicted in Figure 2. There are already commercial versions of such technology, albeit with limited functionality (SCALED | Scaled-Tech, n.d.). The issue for realising the full potential of linkage fabrics for wearable assistive devices is the lack of effective actuators that can be incorporated into a fabric close to the body (Maziz et al., 2017; Nguyen and Zhang, 2020). These actuators are needed for locking and unlocking the device as well as, in the future, to provide active support to limb movement. 3D-printable sensing technology is also a design requirement, which although is available, requires significant development to provide feedback to control systems for this application (Li et al., 2014). Finally, there are challenges in implementing control systems and the required information processing to allow the wearable assistive device to be fully autonomous. We address these challenges in the following sections describing promising future directions for linkage fabrics in terms of the three primary attributes: active, adaptive, and autonomous.

Active

Implementing actuators in wearable assistive materials creates specific design requirements for the actuator material (Hines et al., 2017; Ransley et al., 2017; Ploszajski et al., 2019; Partik et al., 2023). An ideal actuator would need to deliver sufficient actuation strain to facilitate the geometry change of the link and sufficient actuation strength to overcome internal friction. Being electrically actuated would be an advantage since this allows control of individual linkages and thus increases the programmable capabilities of the fabric. However, the application of wearable assistive devices requires low voltages and electronic currents, due to safety issues. Another important factor to consider, as discussed by Ransley et al. (2017) and Nguyen and Zhang (2020), is the effect of actuator hysteresis and responsiveness on the fabric's performance. This is due to the effect that incremental changes at the link level have on the dynamics of the shape change of the whole fabric. In addition to these electrical and mechanical requirements, suitable actuators need to be compatible with the 3D printing technology to allow bespoke linkage fabrics to be produced for individuals. This compatibility means that the actuator needs to be inserted or incorporated into each link either using an additive manufacturing process or equivalent. The sustainability of actuator materials also needs to be considered, ideally with the ability to be separated at the end of life and to be recycled. Taken together, these requirements reduce the viable candidate actuators considerably.

Many material actuators are being developed worldwide, the most relevant to the requirements of animate linkage fabrics are gel-based materials (Kim et al., 2019) and piezoelectric materials (Huang, 2002; Uchino, 2008). However, none of them are ideal. Either their actuation is not electronically controlled, or their actuation strain is too small. Dielectric, conductive, and ionic-metal composite polymers are possible candidates (Kim et al., 2019), but the high actuation voltage is a problem for wearable assistive materials (Romasanta et al., 2015). Conductive and ionic-metal-composite polymer actuators can, in contrast, operate under low voltages (< 10 V) and produce significant strains, as discussed by Kim et al. (2019). However, ionic liquid inside the actuator might evaporate and leak out of the actuator, causing an environmental and health hazard (Rinne et al., 2019). Metal-based actuators such as shape memory alloys, as discussed in the former section, produce the required actuator stress and strains but suffer from a high cooling time and significant hysteresis effects.

In summary, the ideal actuators for animate linkage fabrics do not currently exist, and this is holding back their development into a range of applications such as wearable assistive materials. The development of 3D-printable actuators able to be incorporated into each individual link, operating at low voltages and with low hysteresis effects, while being recyclable would be ideal. Given that none of the current actuators seems to fit these requirements, looking beyond the horizon of the existing actuator materials and perhaps taking inspiration from nature could be a good way forward, such as protein technologies (Siciliano et al., 2018).

Adaptive

Linkage fabrics will require a sensing mechanism if they are to meet their potential as programmable materials. Such a system needs to process information on the state of the fabric, the operation environment, or both. The type and number of stimuli that the structures can potentially sense and respond to will depend on the intended use of the material. For example, in a wearable application, information on the state of the fabric can include pressure, stretch, and torsion, and information on the environment can include temperature, humidity, and the presence of hazardous chemicals. Although environmental cues may form an important part of the functioning of the fabric, further considerations will focus on the sensing of its own state because these sensing techniques are more likely to follow design strategies specific to linkage fabrics.

Sensors for linkage fabrics will need to work with relatively large deformations and multiple degrees of freedom. These requirements are similar to other flexible systems with large ranges of motion, such as smart textiles and soft robots. Sensors that are developed for these systems could therefore be suitable in linkage fabric use. Stretch sensors that are flexible and can measure large strains ($>10\%$) are often made with conductive fabrics (e.g., (Xie et al., 2016; Atalay et al., 2017; Zheng et al., 2020)) or conductive elastomers (e.g., (Shintake et al., 2018; Tairych and Anderson, 2019; Porte and Kramer-Bottiglio, 2021)) as the base material. These type of sensors have been shown suitable for motion tracking (Atalay et al., 2017) and soft robot control (Yuen et al., 2018). Integrating soft sensors into the linkage fabric could be done by adding the sensors to the exterior or by weaving through the linkage structure.

A major challenge for sensing linkage fabrics is the number of sensors that may be required to provide an accurate state estimation of the system. Strains in the system do not have to be continuous due to the discrete links and the linkage structure can take complex shapes with double-curved surfaces.

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

Distributed sensing should be explored to reduce the number of sensors required. In distributed sensing, local strains can be identified without necessarily increasing the number of sensor connections (Gorgutsa et al., 2012; Tomo et al., 2018; Truby et al., 2020). For example, the use of multiple discrete elements that are embedded in a sensor (Levi et al., 2013; Tomo et al., 2018), or performing measurements at a range of frequencies for capacitive sensors (Gorgutsa et al., 2012), can provide additional information on the location of deformations.

However, these sensing strategies do not harness the unique feature of the linkage fabric, that is, that it is made from discrete links that interact without a fixed connection. One of the main deformation modes of a linkage fabric is through the rotation of links compared to their neighbours, which is different than most continuous materials that deform through bending or stretch. We therefore envision the ideal linkage fabric sensing system to be of a similar modular nature where information is shared between the links through the way they are interacting. Although current sensing technologies could be integrated into linkage fabric structures, a sensing system that plays to the strengths of the modularity of the linkage fabric structures still needs to be developed.

Autonomy

Many of the applications of linkage fabrics require the material to change shape in response to a stimulus or to react to environmental change. For instance, a wearable assistive material could respond dynamically to the production of sweat or heat by changing shape and opening cooling channels. Whatever the sensing or actuation required to perform such actions there would need to be a control system with a feedback loop to coordinate the action. This requires a material to have computational capacity, which would also make it possible to make such control autonomous.

This raises the question of how and where information should be processed in linkage fabrics. Most robotic systems have a central processing unit (CPU), often a computer or micro-controller, that processes the inputs and performs the control system according to a predetermined script or a trained algorithm. Converting that concept to linkage fabrics would require each sensor and actuator from each link to be connected to the CPU, perhaps using multiplexing, producing large numbers of physical and data connections between the links and the CPU. This would create a significant complexity within the linkage structure, which also creates a manufacturing challenge of how to fabricate the flexible electrically conductive connections.

An alternative approach would be for each link to act independently, without a central brain, and communicate to the surrounding links through actuation. Such modular computation and control is exhibited widely in the natural world, all plants use this approach. The approach has previously been applied to the self-assembly of small robots into various arrangements and structures (Wei et al., 2010). The work from O'Grady et al. (2010) highlights the ability of these robotic systems to function as a solid entity combining sensing and actuation capabilities. The possible advantages of this approach are a reduced requirement for communication across the whole fabric and increased damage tolerance.

This concept then raises the question of how this processing of information in the links should be handled. Electronic CPUs are the most common way to process information, although there are other ways this can be achieved. Current research using DNA as a medium to store and process information shows promising results as they show the performance of logic gate systems such as 'AND' or 'OR', which can be found at the heart of every computing device we use today (Li et al., 2013). The programming of cells is another exciting idea that has the potential for processing information, although this technology's capabilities are still to be explored (Qian et al., 2018).

Robustness, self-repair, and self-disassembly

All complex multi-cellular living organisms have processes to monitor damage and self-repair. This design principle is likely to be a result of evolutionary pressures in which the investment in increasing

https://doi.org/10.1017/pma.2024.5 Published online by Cambridge University Press

complexity is a survival strategy that only pays off if damage during development is not fatal (Basanta et al., 2008). In contrast, human technology has historically been manually repairable through external actions, usually involving regular maintenance and replacement of parts. However, as complexity has increased, in particular with the development of integrated electronics and software, products have become increasingly difficult to repair (Vanegas et al., 2018; UK Parliament, 2020). In parallel, the development of mass production, which increases the efficiency of production and reduces costs, has made design for obsolescence an increasing strategy adopted by product developers (UK Parliament, 2021). It has led to the decrease in the lifespans of products of household appliances, which are discarded as soon as they break. This development coupled with economic growth has led to mountains of waste and environmental damage. Right to Repair laws have been enacted in many countries to reduce this flow of waste and make products more repairable and durable (UK Parliament, 2021). Another strategy is to develop self-repairing products with increased robustness to damage and longer lifespans.

Linkage fabrics offer the possibility of developing products that adapt and change throughout their lifetime, adjusting to different environments and loading conditions and even repairing themselves when damaged. Biomimetic approaches have been used to reproduce some of these material attributes with some success (Suresh Kumar et al., 2020). Linkage fabrics borrow a fundamental design principle from biological materials, that of a modular structure. In the case of biology, the modular unit is the cell. Bacterial chainmail was first observed by Houwink (1953) who reported a single layer of spherical macromolecules arranged in a repeated hexagonal pattern within the cell wall of the Spirillum bacteria, though it was not possible to infer any greater detail as to its nature. Such detail remained elusive until 1998 when Duda (1998) deduced that the capsid of the bacteriophage HK97 comprised interconnected pentamers and hexamers of polypeptide gp5 and compared the structure to chainmail armour, suggesting that it provided stabilisation to the protein complex despite the molecular capsid being extremely thin. Since then the hypothesis has been further validated (Wikoff et al., 2000) and a wealth of research has revealed protein chainmail to exist within the capsid of numerous viruses (Zhou et al., 2014) and the S-Layer of numerous bacteria (Rad et al., 2015) and archaea (Arbing et al., 2012). Interest in the field has been twofold; studying the composition and permeability of the pathogenic organisms' tough exteriors could lead to more effective disease prevention, while understanding the mechanisms through which protein chainmail self-assembles could catalyse critical breakthroughs in nanotechnology and self-healing structures.

In the case of linkage fabrics, the corollary of cellular modularity is delivered through the individual links. Changes made on a link level, as we demonstrated, allow these fabric structures to adapt their physical properties and also adapt their shape. Once such structures have the ability to be active, adaptive, and autonomous, then it opens the possibility for a linkage fabric structure that could be engineered to detect a damaged link and react to restore the function of the fabric. It could do this in a number of ways. For instance, the surrounding links could change shape to mechanically compensate for the damaged link. Alternatively, each link could be designed to have self-repairing mechanisms (such as thermal annealing), which could be activated once damage has been detected. Such mechanisms will make linkage fabrics more damage tolerant and thus extend the service life of products based on this technology, increasing durability and reducing the environmental impact associated with designed obsolescence. Such self-repairing materials may seem futuristic but we note that there are already examples in commercial use such as self-repairing paints (The Royal Society, 2021).

When designing anything, the end-of-life of materials should always be planned. As discussed in this article, animate material linkage fabrics will be complex in terms of materials composition to obtain the capability of being active, adaptive, and autonomous. These could allow the modular elements to be programmed to disassemble by the end of their life. The actuator would therefore play a crucial part in disassembling the link and potentially itself. This design concept for disassembly has been of interest to product designers for years and has been implemented in some products on the market (Crowther, 2005).

Data availability statement. All data reported in this article are openly available upon request to the authors, including linkage fabric designs.

Funding statement. The work reported in this article was funded by the UCL Centre for Computation, Mathematics and Physics in the Life Sciences and Experimental Biology(CoMPLEX); the UKRI under grant NE/V010735/1 and EP/V011804/1; the UCL Institute of Making; and University College London, which we gratefully acknowledge.

Competing interest. The authors confirm there are no competing interests with regard to the content of this research article.

References

Arbing MA, **Chan S**, **Shin A**, **Phan T**, **Ahn CJ**, **Rohlin L** and **Gunsalus RP** (2012) Structure of the surface layer of the methanogenic archaean Methanosarcina acetivorans. *Proceedings of the National Academy of Sciences* **109**(29), 11812–11817.

Atalay A, **Sanchez V**, **Atalay O**, **Vogt DM**, **Haufe F**, **Wood RJ** and **Walsh CJ** (2017) Batch fabrication of customizable silicone-textile composite capacitive strain sensors for human motion tracking. *Advanced Materials Technologies* **2**, 1700136.

AZDENT Dental Open Coil Springs Niti (n.d.) https://azdentall.com/products/azdent-dental-open-coil-springs-niti-0-010-0-030-1pc-roll?˙pos=3& ˙fid=d1b9789c8& ˙ss=c.

Basanta D, **Miodownik M** and **Baum B** (2008) The evolution of robust development and homeostasis in artificial organisms. *PLoS Computational Biology* **4**(3): e1000030.

Bishop MC and **Coulston JCN** (2006) *Roman Military Equipment from the Punic Wars to the Fall of Rome*. Oxford: Oxbow.

Bottomley I and **Hopson A** (1993) *Arms and Armor of the Samurai: The History of Weaponry in Ancient Japan*. Crescent Books. Available at http://books.google.ie/books?id=csUrAAAAYAAJ.

Bullet Real-Time Physics Simulation (n.d.) *https://pybullet.org/wordpress/*.

Crowther P (2005) Design for disassembly – themes and principles. *Environment Design Guide*, pp. 1–7. http://www.jstor.org/stable/26149108

Cusick GE (1968) 21 – The measurement of fabric drape. *Journal of the Textile Institute* **59**(6), 253–260.

Duda RL (1998) Protein chainmail: Catenated protein in viral capsids. *Cell* **94**(1), 55–60.

Featherstone R (2016) A divide-and-conquer articulated-body algorithm for parallel O(log(n)) calculation of rigid-body dynamics. Part 1: Basic algorithm. *The International Journal of Robotics Research* **18**(9), 867–875. https://doi.org/10.1177/02783649922066619; https://journals.sagepub.com/doi/abs/10.1177/02783649922066619

Flaherty J (2013) Look at These Clothes Made of 3-D Printed Chainmail. Available at https://www.wired.com/2013/12/forget-self-driving-cars-google-is-sponsoring-3-d-printed-fashion/.

Gorgutsa S, **Gu JF** and **Skorobogatiy M** (2012) A woven 2D touchpad sensor and a 1D slide sensor using soft capacitor fibers. *Smart Materials and Structures* **21**, 015010.

Hines L, **Petersen K**, **Lum GZ** and **Sitti M** (2017) Soft actuators for small-scale robotics. *Advanced Materials* **29**(13), 1603483.

Houwink A (1953) A macromolecular mono-layer in the cell wall of spirillum spec. *Biochimica et Biophysica Acta* **10**, 360–366.

Hu Z, **Ahmed A**, **Wan W**, **Watanabe T** and **Harada K** (2023) A stiffness-changeable soft finger based on chain mail jamming. In *Proceedings – IEEE International Conference on Robotics and Automation*. London: IEEE, pp. 7405–7411.

Huang W (2002) On the selection of shape memory alloys for actuators. *Materials & Design* **23**(1), 11–19.

Jiang Y, **Guo R**, **Ma F** and **Shi J** (2019) Cloth simulation for Chinese traditional costumes. *Multimedia Tools and Applications* **78**, 5025–5050.

Kavan L, **Gerszewski D**, **Bargteil AW** and **Sloan P-P** (2011) Physics-inspired upsampling for cloth simulation in games. In *ACM SIGGRAPH 2011 Papers*, pp. 1–10.

Kenkare NS (2005) Three Dimensional Modeling of Garment Drape, p. 263. Available at https://repository.lib.ncsu.edu/handle/1840.16/3548.

Kim J, **Kim JW**, **Kim HC**, **Zhai L**, **Ko H-U** and **Muthoka RM** (2019) Review of soft actuator materials. *International Journal of Precision Engineering and Manufacturing* **20**(12), 2221–2241.

Kock J, **Bradley B** and **Levelle E** (2013) Linkage fabric behavior modeling: A case study of chainmail. In *Advances in Architectural Geometry 2012*. Vienna: Springer, pp. 123–134. Available at https://link.springer.com/chapter/10.1007/978-3-7091-1251-9˙9.

Landau E (2017) Space Fabric' Links Fashion and Engineering. Available at https://www.jpl.nasa.gov/news/space-fabric-links-fashion-and-engineering.

Levi A, **Piovanelli M**, **Furlan S**, **Mazzolai B** and **Beccai L** (2013) Soft, transparent, electronic skin for distributed and multiple pressure sensing. *Sensors (Switzerland)* **13**, 6578–6604.

Li Q, **Chen H**, **Ran Z-Y**, **Castano LM** and **Flatau AB** (2014) Smart fabric sensors and e-textile technologies: A review. *Smart Materials and Structures* **23**(5), 053001. Available at https://iopscience.iop.org/article/10.1088/0964-1726/23/5/053001 https://iopscience.iop.org/article/10.1088/0964-1726/23/5/053001/meta.

Li W, **Yang Y**, **Yan H** and **Liu Y** (2013) Three-input majority logic gate and multiple input logic circuit based on DNA strand displacement. *Nano Letters* **13**(6), 2980–2988.

Maziz A, **Concas A**, **Khaldi A**, **Stålhand J**, **Persson NK** and **Jager EW** (2017) Knitting and weaving artificial muscles. *Science Advances* **3**(1), e1600327.

Meng Y, **Mok PY** and **Jin X** (2010) Interactive virtual try-on clothing design systems. *Computer-Aided Design* **42**(4), 310–321.

Nabaei S, **Baverel O** and **Weinand Y** (2015) Form finding of twisted interlaced structures: A hybrid approach. In *Advances in Architectural Geometry 2014*. Cham: Springer, pp. 127–143.

Nguyen PH and **Zhang W** (2020) Design and computational modeling of fabric soft pneumatic actuators for wearable assistive devices. *Scientific Reports* **10**(1), 1–13.

NVIDIA PhysX System Software (n.d.) https://www.nvidia.com/en-us/drivers/physx/physx-9-19-0218-driver/.

O'Grady R, **Groß R**, **Christensen AL** and **Dorigo M** (2010) Self-assembly strategies in a group of autonomous mobile robots. *Autonomous Robots* **28**(4), 439–455.

Partik C, **Porte E**, **Purkiss D**, **Michalska M** and **Miodownik M** (2023) The use of phase change material as an actuator in linkage fabric structures. *Frontiers in Materials* **10**, 1268975. Available at https://www.frontiersin.org/articles/10.3389/fmats.2023.1268975/full.

Ploszajski A, **Jackson R**, **Ransley M** and **Miodownik M** (2019) 4D printing of magnetically functionalized chainmail for exoskeletal biomedical applications. *MRS Advances* **4**(23), 1361–1366.

Porte E and **Kramer-Bottiglio R** (2021) Nonlinear Poisson's ratio for modeling hyperelastic capacitive sensors. *Advanced Materials Technologies* **6**. https://doi.org/10.1002/admt.202001247

Project Chrono (n.d.) *https://projectchrono.org/*.

Qian Y, **McBride C** and **Del Vecchio D** (2018) Programming cells to work for us. *Annual Review of Control, Robotics, and Autonomous Systems* **1**(1), 411–440.

Rad B, **Haxton TK**, **Shon A**, **Shin S-H**, **Whitelam S** and **Ajo-Franklin CM** (2015) Ion-specific control of the self-assembly dynamics of a nanostructured protein lattice. *ACS Nano* **9**(1), 180–190.

Ransley M (2023) Architectured materials for wearable assistive technology. Ph.D. thesis, University College London.

Ransley M, **Smitham P** and **Miodownik M** (2017) Active chainmail fabrics for soft robotic applications. *Smart Materials and Structures* **26**(8), 08LT02. https://doi.org/10.1088/1361-665X/aa7221

Rinne P, **Poldsalu I**, **Johanson U**, **Tamm T**, **Pohako-Esko K**, **Punning A**, **Van Den Ende D** and **Aabloo A** (2019) Encapsulation of ionic electromechanically active polymer actuators. *Smart Materials and Structures* **28**(7), 074002.

Romasanta LJ, **López-Manchado MA** and **Verdejo R** (2015) Increasing the performance of dielectric elastomer actuators: A review from the materials perspective. *Progress in Polymer Science* **51**, 188–211.

Rudykh S, **Ortiz C** and **Boyce MC** (2015) Flexibility and protection by design: Imbricated hybrid microstructures of bio-inspired armor. *Soft Matter* **11**(13), 2547–2554. Available at https://pubs.rsc.org/en/content/articlehtml/2015/sm/c4sm02907k https://pubs.rsc.org/en/content/articlelanding/2015/sm/c4sm02907k.

SCALED – Scaled-Tech (n.d.) https://www.scaled-tech.com/.

Shintake J, **Piskarev E**, **Jeong SH** and **Floreano D** (2018) Ultrastretchable strain sensors using carbon black-filled elastomer composites and comparison of capacitive versus resistive sensors. *Advanced Materials Technologies* **3**, 1700284.

Siciliano V, **DiAndreth B**, **Monel B**, **Beal J**, **Huh J**, **Clayton KL**, **Wroblewska L**, **McKeon A**, **Walker BD** and **Weiss R** (2018) Engineering modular intracellular protein sensor-actuator devices. *Nature Communications* **9**(1), 1881.

Sim D (1997) Roman chain-mail: Experiments to reproduce the techniques of manufacture. *Britannia* **28**, 359–371. Available at https://www.jstor.org/stable/526776#metadata_info_tab_contents.

Suresh Kumar N, **Padma Suvarna R**, **Chandra Babu Naidu K**, **Banerjee P**, **Ratnamala A** and **Manjunatha H** (2020) A review on biological and biomimetic materials and their applications. *Applied Physics A* **126**(6), 1–18.

Tairych A and **Anderson IA** (2019) Capacitive stretch sensing for robotic skins. *Soft Robotics* **6**, 389–398.

The Royal Society (2021) *Animate materials*. Technical report 7, the Royal Society.

Tian Y, **Chen K**, **Zheng H**, **Kripalani DR**, **Zeng Z**, **Jarlöv A**, **Chen J**, **Bai L**, **Ong A**, **Du H**, **Kang G**, **Fang Q**, **Zhao L**, **Qi HJ**, **Wang Y** and **Zhou K** (2023) Additively manufactured dual-faced structured fabric for shape-adaptive protection. *Advanced Science* **10**(21), 2301567. Available at https://onlinelibrary.wiley.com/doi/full/10.1002/advs.202301567; https://onlinelibrary.wiley.com/doi/abs/10.1002/advs.202301567; https://onlinelibrary.wiley.com/doi/10.1002/advs.202301567.

Tomo TP, **Schmitz A**, **Wong WK**, **Kristanto H**, **Somlor S**, **Hwang J**, **Jamone L** and **Sugano S** (2018) Covering a robot fingertip with uSkin: A soft electronic skin with distributed 3-axis force sensitive elements for robot hands. *IEEE Robotics and Automation Letters* **3**, 124–131.

Truby RL, **Santina CD** and **Rus D** (2020) Distributed proprioception of 3D configuration in soft, sensorized robots via deep learning. *IEEE Robotics and Automation Letters* **5**, 3299–3306.

Uchino K (2008) Piezoelectric actuators 2006. *Journal of Electroceramics* **20**(3), 301–311.

UK Parliament (2020) Electronic Waste and the Circular Economy. Available at https://researchbriefings.files.parliament.uk/documents/CBP-9302/CBP-9302.pdf.

UK Parliament (2021) Right to Repair Regulations Briefing. Available at https://publications.parliament.uk/pa/cm5801/cmselect/cmenvaud/220/22006.htm#::text.

Vanegas P, **Peeters J**, **Cattrysse D**, **Tecchio P**, **Ardente F**, **Mathieux F**, **Dewulf W** and **Duflou J** (2018) Ease of disassembly of products to support circular economy strategies. *Resources, Conservation and Recycling* **135**, 323–334.

Wang Y, **Li L**, **Hofmann D**, **Andrade JE** and **Daraio C** (2021) Structured fabrics with tunable mechanical properties. *Nature* **596**(7871), 238–243. Available at https://www.nature.com/articles/s41586-021-03698-7.

Wei H, **Cai Y**, **Li H**, **Li D** and **Wang T** (2010) Sambot: A self-assembly modular robot for swarm robot. In *2010 IEEE International Conference on Robotics and Automation*. IEEE, pp. 66–71.

Wikoff WR, **Liljas L**, **Duda RL**, **Tsuruta H**, **Hendrix RW** and **Johnson JE** (2000) Topologically linked protein rings in the bacteriophage HK97 capsid. *Science* **289**(5487), 2129–2133.

Xie J, **Long H** and **Miao M** (2016) High sensitivity knitted fabric strain sensors. *Smart Materials and Structures* **25**, 105008.

Xu J, **Zhang Y**, **Huang Y**, **Chang L**, **Chen T**, **Ren T** and **Cai Z** (2023) Dynamic response of chain mail fabrics with variable stiffness. *International Journal of Mechanical Sciences* **264**, 108840.

Yuen MCS, **Lear TR**, **Tonoyan H**, **Telleria M** and **Kramer-Bottiglio R** (2018) Toward closed-loop control of pneumatic grippers during pack-and-deploy operations. *IEEE Robotics and Automation Letters* **3**, 1402–1409.

Zheng Y, **Li Y**, **Zhou Y**, **Dai K**, **Zheng G**, **Zhang B**, **Liu C** and **Shen C** (2020) High-performance wearable strain sensor based on graphene/cotton fabric with high durability and low detection limit. *ACS Applied Materials and Interfaces* **12**, 1474–1485.

Zhou ZH, **Hui WH**, **Shah S**, **Jih J**, **O'Connor CM**, **Sherman MB**, **Kedes DH** and **Schein S** (2014) Four levels of hierarchical organization, including noncovalent chainmail, brace the mature tumor herpesvirus capsid against pressurization. *Structure* **22**(10), 1385–1398.

Cite this article: Ransley, M., Partik, C., Porte, E., Ploszajski, A., Jackson, R., Oldfrey, B., Purkiss, D., Michalska, M., and Miodownik, M. (2024). An introduction to linkage fabrics and their application as programmable materials. *Programmable Materials*, **2**, e5. https://doi.org/10.1017/pma.2024.5