

Effect of load orientation and weave pattern on the mechanical properties of woven active textiles for the design of wearable devices and soft actuators

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Abstract

Active textiles featuring pneumatic actuators, such as thin McKibben muscles, enable tunable stiffness, which is desirable for soft robotics, but the characterisation of their mechanical properties, particularly with respect to load orientation and weave pattern, remains lacking. Consequently, this paper ascertains the mechanical properties of active textiles, crucial for real-world scenarios, with unevenly distributed strains often misaligned with the weave pattern. The results show that: (i) tensile properties exhibit a hysteretic behaviour, with a maxima at 0.05 MPa during pressurisation and a minima at 0.15 MPa during depressurisation and a reduction in tensile modulus for increasing rotation angle; (ii) greater tensile properties are achieved by minimising the warp's deviation from straightness, via weave pattern or reduction in muscle density; (iii) flexural properties require both a non-zero pressure and rotation angle greater than 15° to exhibit meaningful flexural properties, reaching circa 30 MPa at 90°; and (iv) where out-of-plane curvature occurs, flexural properties are significantly affected by the concave face's orientation. Ultimately, tensile properties are driven by the warp's alignment with the load, while flexural properties are driven by the weft's alignment with the load. These findings provide novel insights into the mechanical properties and design optimisation of active textiles.

Keywords

thin McKibben muscle, pneumatic actuator, active textile, fluidic textile, soft robotics

Introduction

Active textiles, also referred to as functional fabrics, employ soft, deformable materials for soft robotics applications, with motion being triggered electromechanically, as tackled in the reviews of Hu et al. (2012), Castano and Flatau (2014), Stoppa and Chiolerio (2014), Mirvakili and Hunter (2018), Mun et al. (2018), Xiong et al. (2021), Chen et al. (2023), Xu et al. (2024), and Li et al. (2024). More recently, fluidic textiles and textile actuators (Chen et al., 2021), such as pneumatic artificial muscles or thin McKibben muscles (Kurumaya et al., 2017), have demonstrated their potential and versatility for soft robotic applications (Hiramitsu et al., 2019). These range from wearable technologies for high-performance or health-assistive purposes to industrial manipulation, exploiting the short response time and high-power density of such fluidic textiles (Pagoli et al., 2022; Ten Bhömer et al., 2016; Younes et al., 2016; Zhu et al., 2020).

The fibre-like nature of thin McKibben muscles (Salahuddin et al., 2021; Wirekoh and Park, 2017) is

particularly suited to biomimicry and musculoskeletal robots (Na et al., 2023). Employed in a parallel arrangement of filaments, these replicate the tensile effects of biological muscles, for instance, for human (Garriga-Casanovas et al., 2017; Vraitch et al., 2024) and mammal (Niikura et al., 2022) necks. When woven, active textiles enable non-homogeneous and asymmetric stiffening, leading to flexion and curvature. Similar to knitted active textiles (Abel et al., 2013; Eschen et al., 2020), woven active textiles have been extensively studied to investigate how weave patterns and the non-actuated textiles employed affect the overall shape

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Data Availability Statement included at the end of the article



Figure 1. (a) Woven active textiles (reproduced from Hiramitsu et al., 2023), and application of fluidic actuators to (b) human neck (reproduced from Garriga-Casanovas et al., 2017), (c) ankle-foot orthosis (reproduced from Thalman et al., 2022), (d) upper limb rehabilitation device (reproduced from Greig et al., 2025), and (e) exo-suits (reproduced from Christensen et al., 2021).

changes for varying pressures (Hiramitsu et al., 2023; Koizumi et al., 2018; Kurumaya et al., 2017). This is particularly relevant to safely meet the needs of human-centred robotics (Andreasson et al., 2018; Thalman and Artemiadis, 2020), wearables such as rehabilitation equipment (Diteesawat et al., 2022; Greig et al., 2025; Thalman et al., 2022), exo-suits (Christensen et al., 2021; Pulvirenti et al., 2022; Talukder and Jo, 2025) and even soft myocardial bands (Ueda et al., 2025). The versatility of active textiles and McKibben muscles is demonstrated in Figure 1.

However, a lack of characterisation of the mechanical properties of pneumatically actuated active textiles hinders their wider application in wearable devices, particularly for multi-degree-of-freedom systems, where tunable properties are desirable. Indeed, only recently were the mechanical properties (tensile and flexural modulus) of a plain-weave active textile quantified (Marshall et al., 2023) for varying input pressures. These findings identified a strong dependency on muscle density in tension; however, they were less conclusive in flexion. This limitation was attributed to the single load orientation tested not being most suitable to exhibit flexural properties. Indeed, the typical arrangement of woven structure is such that forces are never applied directly in-line, or tangentially to the fibres, but at some angle. Moreover, the work of Marshall et al. (2023) investigated a plain weave, which would not result in out-of-plane curvature. This is in contrast to Hiramitsu et al. (2023), who tackled the effect of the weave pattern on out-of-plane curvature but did not

quantify the mechanical properties. As such, there remains a critical need to characterise the mechanical properties of active textiles for varying load orientations, and for weaves able to exhibit out-of-plane curvature, in order to meet the demand for complex, human-centred, multi-degree-of-freedom wearables.

Given the wide range and versatile applications of active textiles, a greater understanding of their mechanical properties and variations with load orientation and weave pattern is needed to support developments in soft robotics and wearables. Consequently, this paper furthers the recent work of Hiramitsu et al. (2023) and Marshall et al. (2023) by characterising the tensile and flexural properties of an active textile in line with relevant ISO (International Organization for Standardization) standards for tension (International Organization for Standardization (ISO), 2012) and flexion (ISO, 2019), respectively, to ensure the reliability and repeatability of the results, for a range of orientation angles. Additionally, the same mechanical properties are assessed for a 2 by 1 twill (or prunelle) weave. The aim is to expand the current knowledge of active textiles and their mechanical properties for two previously unstudied variables: load orientation and weave pattern.

The remainder of this paper is structured as follows. First, the woven pneumatic active textiles investigated are detailed. Then, the experimental protocol, quantification of the mechanical properties and associated uncertainty are covered. Moreover, the mechanical properties of the active textiles are characterised, in both tension and flexion, and the significance of these results is discussed. Ultimately, the main findings are summarised.

Active textiles

Two separate active textiles are manufactured and investigated in this study:

- a 200 mm long by 200 mm wide square sample with a plain weave, subsequently denoted as T_1 , to investigate the effect of load orientation; and
- a 200 mm long by 50 mm wide rectangular sample with a prunelle (or 2 by 1 twill), labelled T_2 , to investigate the effect of the weave pattern.

The dimensions of T_2 are in accordance with the ISO 13934-1:2013 (ISO, 2013) for textiles, namely a woven gauge length $L_0 = 200$ mm and width $b = 50$ mm, which are identical to the dimension of Marshall et al. (2023). On the other hand, T_1 features a larger width $b = 200$ mm to enable rotation of the sample in both tension and flexion, thereby remedying the limitations of previous work (Marshall et al., 2023), and further detailed in the Methods section. The plain weave and

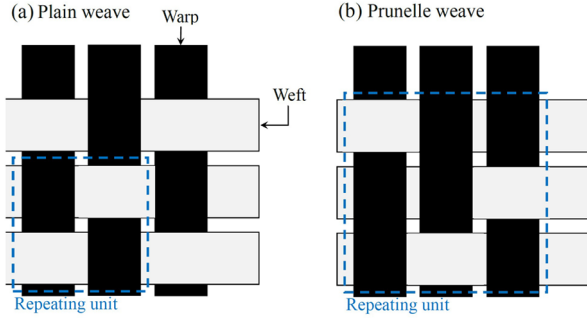


Figure 2. Schematic of (a) the plain weave pattern employed for T_1 and (b) the prunelle (2 by 1 twill) weave pattern used for T_2 .

prunelle weave are depicted in Figure 2(a) and (b), respectively.

The active textiles manufactured are made of a warp and a weft woven normal to it. The weave patterns adopted are depicted schematically in Figure 2. A 1.50 mm nominal diameter Nylon 6 (polyamide) constitutes the warp, with a measured 0.78 gm^{-1} mass per unit length and a 520.00 gm^{-2} mass per unit surface area. A thin McKibben pneumatic artificial muscle (EM20 McKibben S-muscle) is employed for the weft. It is a combination of 32 polyethylene terephthalate monofilament spindles for the outer sleeve (19° angle and 0.16 mm nominal diameter) and a synthetic rubber tube for the inner bladder (2.20 mm outer diameter, 0.20 mm wall thickness). Unpressurised, that is, for an input pressure $P = 0.00 \text{ MPa}$, the weft has a $D_0 = 3.00 \text{ mm}$ nominal outer diameter, with a 2.44 gm^{-1} mass per unit length and a 813.33 gm^{-2} mass per unit surface area. To alleviate the Mullins effect (Hocking and Wereley, 2013), where the stress-strain curve of rubbers depends on the previously encountered maximum load, the pneumatic muscle is first taken through a cycle of incremental input pressure from $P = 0.00 \text{ MPa}$ to $P = 0.50 \text{ MPa}$ in $P = 0.10 \text{ MPa}$ increment, with each increment being repeated twice.

The active textiles are tested for different muscle densities ρ_M , namely $\rho_M = 100 \text{ m}^{-1}$ for T_1 and $\rho_M = 100 \text{ m}^{-1}$, $\rho_M = 74.26 \text{ m}^{-1}$ and $\rho_M = 47.62 \text{ m}^{-1}$ for T_2 . Here, ρ_M is defined as

$$\rho_M = \frac{1}{s_{\text{weft}} [\text{m}]} = \frac{n_{\text{weft}}}{L_0 [\text{m}]}, \quad (1)$$

where s_{weft} is the lengthwise weft spacing, n_{weft} is the lengthwise number of weft and L_0 is the gauge length.

The manufactured T_1 is made of 136 strands for the warp, see Figure 3(a), while T_2 is made of 34 strands for the warp (identical to that of Marshall et al., 2023). Both woven T_1 and T_2 at $\rho_M = 100 \text{ m}^{-1}$ are 300 mm long overall, made of a woven gauge length $L_0 = 200 \text{ mm}$ at $P = 0.00 \text{ MPa}$ and two 50 mm long

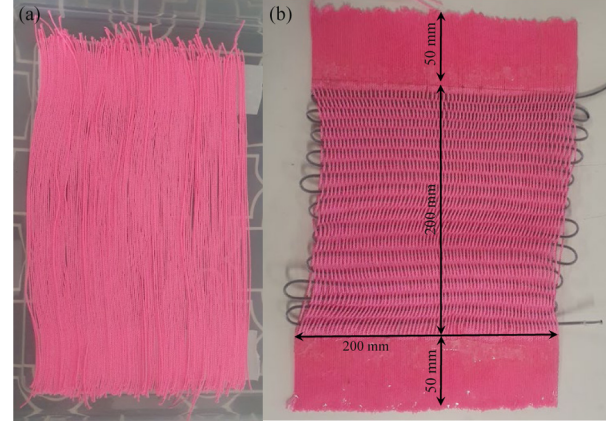


Figure 3. T_1 active textile (a) prior to manufacturing, and (b) after manufacturing, including annotated dimensions.

tabs reinforced with epoxy resin at each lengthwise end. This is depicted in Figure 3(b). To achieve a woven $L_0 = 200 \text{ mm}$ at the maximum muscle density ($\rho_M = 100 \text{ m}^{-1}$), an unwoven $L = 215 \text{ mm}$ is necessary. The width b_0 is 200 mm and the thickness h_0 is 6.00 mm, both at $P = 0.00 \text{ MPa}$.

Methods

Experimental setup and protocol

All experiments were performed on an Instron 5965 fitted with a 500 N load cell and were conducted at temperatures $20.1^\circ\text{C} \leq T \leq 26.3^\circ\text{C}$ and relative humidities $0.35 \leq \phi \leq 0.57$. To suppress any slack in the sample, a preload of 1 N in tension and 0.02 N in flexion is applied at a displacement rate of 10 mm min^{-1} . Past the preload threshold, force and displacement (elongation in tension, deflection in flexion) are then recorded at 200 Hz for a displacement rate of 1 mm min^{-1} . To prevent any plastic deformation that may affect the textile's mechanical properties, all experiments are conducted only up to a strain $\epsilon = 0.003$.

The tensile setup is depicted in Figure 4(a) for T_1 at a rotation angle $\theta = 0^\circ$, where θ is defined as the angle between either the lengthwise direction in tension, or spanwise direction in flexion, and the warp direction, see Figure 4(b). Tensile tests for T_1 were conducted at $\theta = 0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ, 25^\circ$ and 30° . This range is limited by the ability to clamp the end tabs. Conversely, in flexion, a wider range of angles could be investigated for T_1 , namely $\theta = 0^\circ, 7.5^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 82.5^\circ$ and 90° , using a 3-point bend test with a span $s = 120 \text{ mm}$. The load point and two support points have a 50 mm width. For T_2 , shown pre- and post-weaving in Figure 5(a), both the tensile and flexural setups are identical to that of T_1 , albeit only at $\theta = 0^\circ$, thus being identical to Marshall et al. (2023). The flexural setup is depicted in Figure 5(b) for the plain

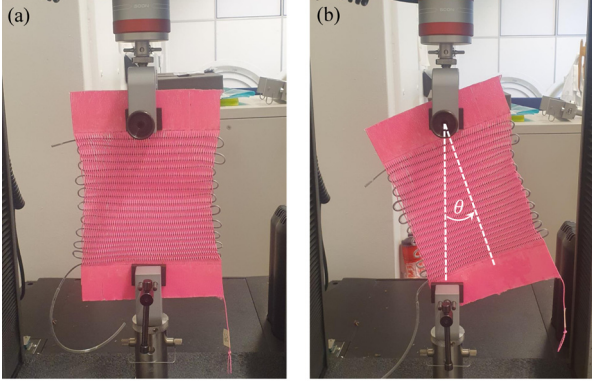


Figure 4. Tensile setup at (a) $\theta = 0^\circ$ and (b) definition of θ .

weave. However, because of the prunelle weave adopted and associated out-of-plane curvature, flexural experiments were repeated both with the concave side upwards (denoted as $\cup$) and downwards (denoted as $\cap$) to capture the effect of the geometrical deformation on the mechanical properties.

Tensile and flexural properties

The tensile properties are ascertained based on the ISO 527-2:2012 (ISO, 2012). First, the tensile strain ϵ is computed based on the measured elongation ΔL_0 such that

$$\epsilon = \frac{\Delta L_0}{L_0}. \quad (2)$$

Then, the tensile stress σ is given as

$$\sigma = \frac{F}{bh}, \quad (3)$$

where F is the force and h is the textile thickness.

Finally, the tensile (or Young's) modulus E is ascertained

$$E = \frac{\sigma}{\epsilon}. \quad (4)$$

Based on the ISO 178:2019 (ISO, 2019), the flexural strain ϵ_f , flexural stress σ_f and flexural modulus E_f are given in equations (5)–(7), respectively, such that

$$\epsilon_f = \frac{6wh}{s^2}, \quad (5)$$

$$\sigma_f = \frac{3Fs}{2bh^2}, \quad (6)$$

and

$$E_f = \frac{\sigma_f}{\epsilon_f}, \quad (7)$$

where w is the deflection.

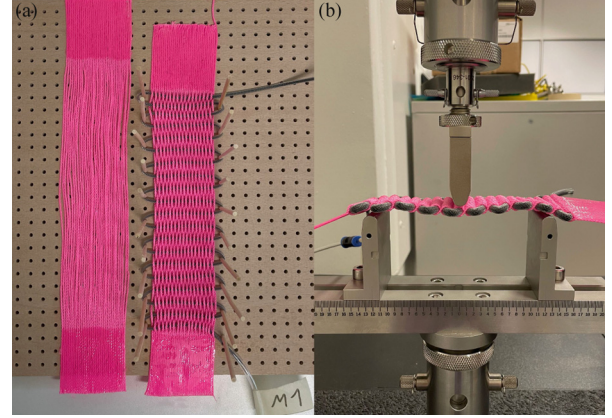


Figure 5. Example of plain weave active textile (reproduced from Marshall et al., 2023) (a) during manufacturing, namely pre- and post-weaving, showing the reduction in length and (b) during flexural testing.

Both moduli are computed using the linear least squares method for $0.0005 \leq \epsilon \leq 0.0025$ and $0.0005 \leq \epsilon_f \leq 0.0025$, as per ISO 178 (ISO, 2019). Because the mechanical properties are a function of the geometrical properties, varying with the input pressure, the geometrical characteristics of the active textile will be quantified for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$. Experiments are conducted up to $P = 0.50 \text{ MPa}$, similar to the recent work of Na et al. (2023) and Hiramitsu et al. (2023), but in contrast to Marshall et al. (2023) which quantified tensile and flexural properties up to $P = 0.60 \text{ MPa}$. This is because significant muscle bursting was experienced for $P > 0.50 \text{ MPa}$, which has prompted further research into the durability of thin McKibben muscles (Kobayashi et al., 2024). Lastly, for the purpose of the stress calculations, see equations (3) and (6), only a 50 mm wide strip out of the overall 200 mm width of the sample is considered to be loaded. This corresponds to the width of tensile jaws clamping the sample in tension, and the width of the loading and support points in the flexural 3-point bend setup. This assumption will later be shown to yield a good agreement with the experiments undertaken by Marshall et al. (2023) on 50 mm wide samples.

Uncertainty quantification

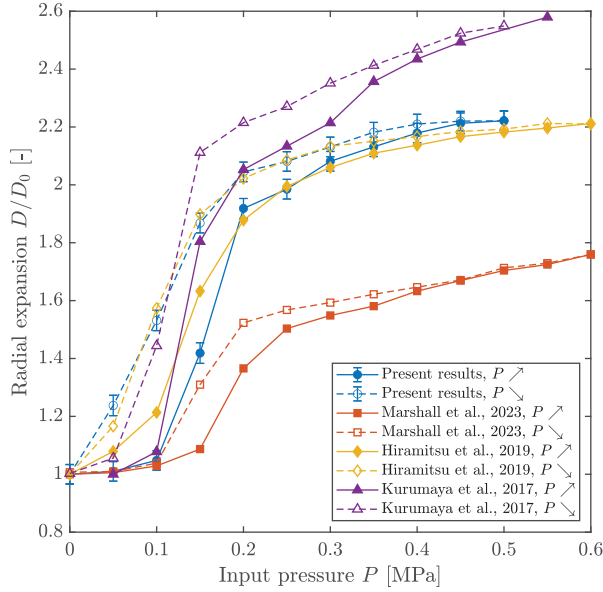
The uncertainty U associated with the results presented in the Results section, represented by error bars, is quantified using the methodology applied to composite materials by Soupez and Laci (2022) and active textiles by Marshall et al. (2023), namely

$$U = \sqrt{(B^2 + P_r^2)}, \quad (8)$$

where the bias $B(X)$ of a quantity X based on a number N of independent variables x_i with a bias limit $B(x_i)$, as listed in Table 1, is

Table 1. Summary of the bias limits.

Elongation, $B(\Delta L_0)$ (mm)	0.00005
Length, $B(L_0)$ (mm)	0.5
Force, $B(F)$ (N)	0.00005
Width, $B(b)$ (mm)	0.005
Thickness, $B(h)$ (mm)	0.005
Deflection, $B(w)$ (mm)	0.00005
Span, $B(s)$ (mm)	0.005

**Figure 6.** Radial expansion D/D_0 of the pneumatic muscle for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$ compared to data from Marshall et al. (2023), Hiramitsu et al. (2019) and Kurumaya et al. (2017).

$$B(X) = \left[\sum_{i=1}^N \left(\frac{\partial X}{\partial x_i} B(x_i) \right)^2 \right]^{\frac{1}{2}}, \quad (9)$$

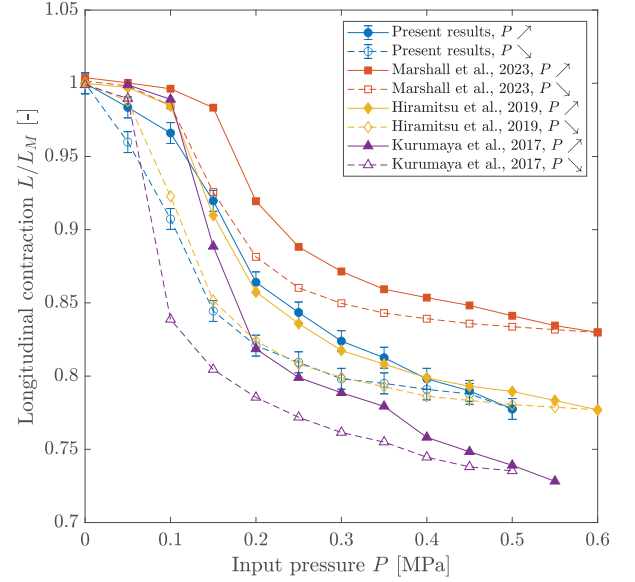
and the precision P_r based on the standard deviation σ_{dev} at the 95% confidence level, is

$$P_r = \frac{t_{95} \sigma_{\text{dev}}}{\sqrt{n}}, \quad (10)$$

where $t_{95} = 2.776$ for the $n = 5$ repeats (as dictated by ISO standards (ISO, 2012, 2019)) undertaken, each active textile (T_1 and T_2) being tested 5 separate times.

Results and discussion

The results section is structured as follows. First, a characterisation of both the pneumatic artificial muscle (weft) and active textiles T_1 and T_2 is offered. Secondly, the effect of load orientation by studying textile T_1 is addressed. Then, the effect of the weave pattern is tackled by investigating textile T_2 . Ultimately, the novel insights gathered on the effect of load orientation and

**Figure 7.** Longitudinal contraction L/L_M of the pneumatic muscle for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$ compared to data from Marshall et al. (2023), Hiramitsu et al. (2019) and Kurumaya et al. (2017).

weave pattern, as well as their implications for wearable devices and soft actuators, are discussed.

Weft and active textile characterisation

Weft characterisation. The radial expansion D/D_0 and longitudinal contraction L/L_M of the weft alone are first characterised as a function of the measured diameter D , length L and unwoven and unpressurised muscle length L_M , for monotonically increasing ($P \nearrow$) and monotonically decreasing ($P \searrow$) pressures. The radial expansion presented in Figure 6 shows a strong agreement with the findings of Hiramitsu et al. (2019), not only in quantitative magnitude but also in qualitative behaviour. Indeed, the hysteretic behaviour of thin McKibben muscle, critical in soft robotic actuation to ensure symmetrical response under duty cycles, is most prominent for $0.05 \text{ MPa} \leq P \leq 0.20 \text{ MPa}$, before a gradual tapering off. This is compared to the hysteresis of Marshall et al. (2023) and Kurumaya et al. (2017), occurring primarily for $0.20 \text{ MPa} \leq P \leq 0.35 \text{ MPa}$ and $0.10 \text{ MPa} \leq P \leq 0.35 \text{ MPa}$, respectively.

Similarly, the longitudinal contraction depicted in Figure 7 yields identical findings, including a strong agreement with the data of Hiramitsu et al. (2019). Nevertheless, the differences with the results of Marshall et al. (2023) and Kurumaya et al. (2017) demonstrate that the accurate prediction of the geometry of thin McKibben muscles under varying air pressures remains a challenge in soft robotics (Hiramitsu et al., 2023) and thus warrant the geometrical characterisation of the active textile.

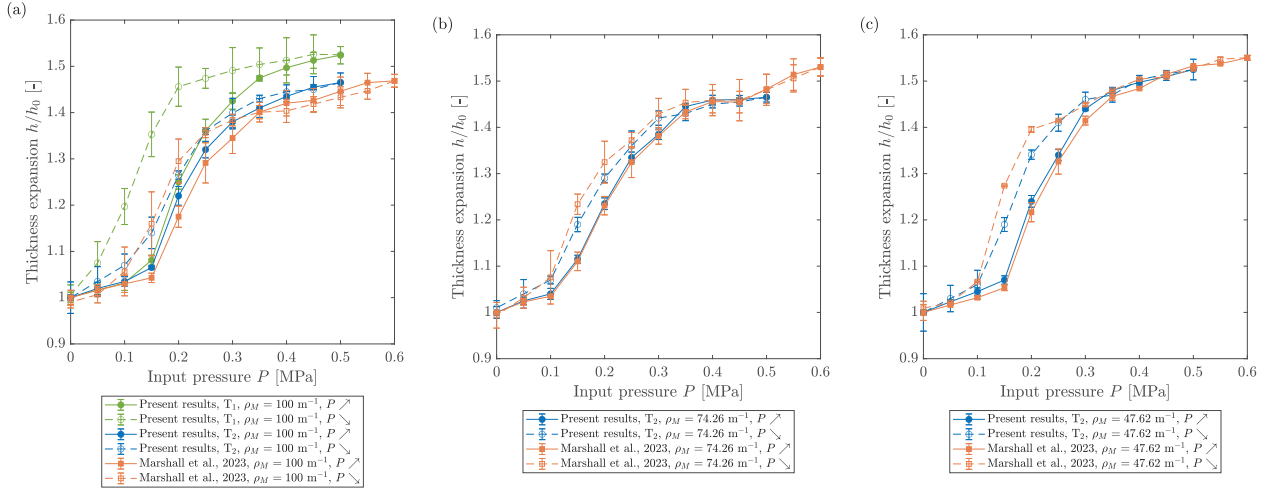


Figure 8. Thickness expansion h/h_0 of the woven active textiles for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$ compared to data from Marshall et al. (2023) at (a) $\rho_M = 100 \text{ m}^{-1}$ for T_1 and T_2 , (b) $\rho_M = 74.26 \text{ m}^{-1}$ for T_2 and (c) $\rho_M = 47.62 \text{ m}^{-1}$ for T_2 .

Active textile characterisation. For the range of pressures investigated, the thickness h and length L of the woven active textiles are measured to compute the thickness expansion h/h_0 and the longitudinal contraction L/L_0 . These are presented in Figures 8 and 9, respectively. Contrary to the previous Section, which quantified the weft's diameter and length, here, the textile thickness also includes the warp, either side of the weft and the length excludes end tabs.

The present textiles (T_1 and T_2), similar to that of Marshall et al. (2023), both continue to exhibit a hysteretic behaviour, driven by that of the weft. For T_1 , there is a markedly greater thickness expansion and lesser longitudinal contraction compared to Marshall et al. (2023) for the same plain weave at $\rho_M = 100 \text{ m}^{-1}$. Because this is the highest practical muscle density for this textile and weave, there is insufficient room for longitudinal contraction to take place to its full extent, which, consequently, drives a higher thickness expansion. For T_2 , the present prunelle weave exhibits a similar thickness expansion compared to the plain weave of Marshall et al. (2023) (Figure 8), but with greater longitudinal contraction (Figure 9), owing to the out-of-plane curvature. Indeed, at $P = 0.50 \text{ MPa}$ and $\rho_M = 100 \text{ m}^{-1}$, T_2 values of $h/h_0 = 1.465$ and $L/L_0 = 0.768$ compared to $h/h_0 = 1.446$ and $L/L_0 = 0.832$ ($P \nearrow$) and $h/h_0 = 1.443$ and $L/L_0 = 0.825$ ($P \searrow$) for Marshall et al. (2023).

The present results for T_2 also identify a comparatively higher uncertainty for $P \searrow$ compared to $P \nearrow$, for both h/h_0 and L/L_0 . This behaviour is absent for the weft, suggesting it arises from the interference and friction between the weft and warp, particularly at the high muscle density $\rho_M = 100 \text{ m}^{-1}$, which is the highest practical ρ_M achievable for this textile. Indeed, at a higher muscle density, there is less free space for recovery during depressurisation, and interfacial friction and

space constraints induce greater uncertainty from sample to sample. A similar observation can be made in the results of Marshall et al. (2023) who investigated three muscle densities, namely $\rho_M = 100 \text{ m}^{-1}$, 74.26 m^{-1} and 47.62 m^{-1} : a comparatively higher uncertainty for $P \searrow$ compared to $P \nearrow$ is found at $\rho_M = 100 \text{ m}^{-1}$ but absent at 74.26 m^{-1} and 47.62 m^{-1} . Consequently, a muscle density that is too high may lead to increased uncertainty at decreasing pressures and thus affect the ability to consistently and accurately predict the active textile response under duty cycles. We then provide the first characterisation of the tensile and flexural properties of an active textile for varying orientations of the applied load.

Effect of orientation

This section focuses on textile T_1 only (200 mm length by 200 mm width, $\rho_M = 100 \text{ m}^{-1}$) to understand the effect of load orientation of active textiles.

Tensile properties. While Marshall et al. (2023) reported on the tensile properties of a plain-woven active textile, the effect of the rotation angle remains uncharacterised. This information is of crucial importance for the design of wearable devices in real-world settings where load application is rarely aligned with the warp or weft arrangements. From the present experiment, the effect of θ on the tensile modulus is presented in Figure 10 for $0^\circ \leq \theta \leq 30^\circ$, that is, the range practically achievable for the clamping method employed. First, consider the results at $\theta = 0^\circ$ compared to that of Marshall et al. (2023). For $0.00 \text{ MPa} \leq P \leq 0.35 \text{ MPa}$, an identical trend is identified, with values between the joint uncertainty of both experiments (error bars in Figure 10 omitted for clarity), including a maximum at

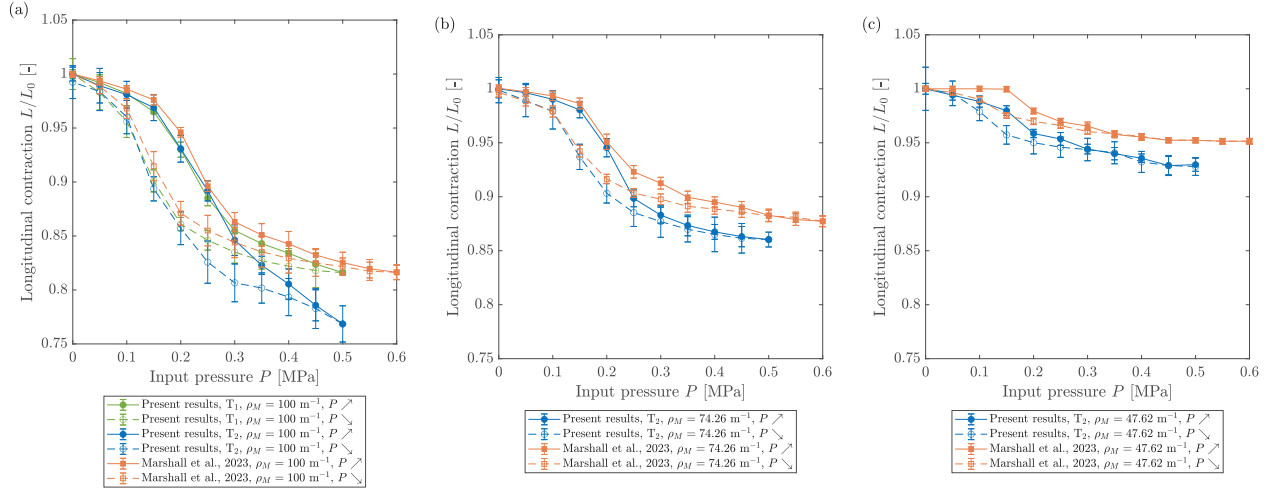


Figure 9. Longitudinal contraction L/L_0 of the woven active textile for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$ compared to data from Marshall et al. (2023) at (a) $\rho_M = 100 \text{ m}^{-1}$ for T_1 and T_2 , (b) $\rho_M = 74.26 \text{ m}^{-1}$ for T_2 and (c) $\rho_M = 47.62 \text{ m}^{-1}$ for T_2 .

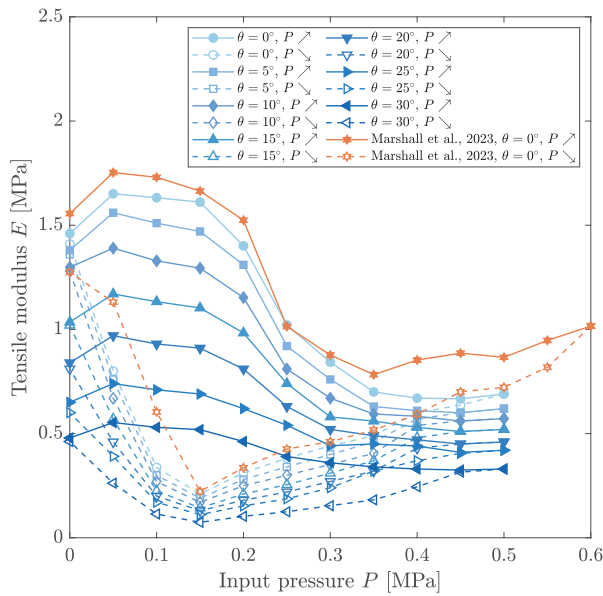


Figure 10. Tensile modulus E of the T_1 woven active textile ($L_0 = 200 \text{ mm}$, $b = 200 \text{ mm}$) for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$ compared to data from Marshall et al. (2023) ($L_0 = 200 \text{ mm}$, $b = 50 \text{ mm}$) at $\theta = 0^\circ$. Error bars omitted for clarity.

$P = 0.05 \text{ MPa}$ for $P \nearrow$ and a minimum at $P = 0.15 \text{ MPa}$ for $P \searrow$. The marginally higher values of E for Marshall et al. (2023) are consistent with the textile characterisation (Figure 8): the higher h/h_0 of the present T_1 textile compared to that of Marshall et al. (2023) results in a greater misalignment of the warp with the direction of tensile load. Because the warp drives the tensile properties, this results in a lower tensile modulus compared to Marshall et al. (2023). For $P \geq 0.40 \text{ MPa}$, a different behaviour is identified: while Marshall et al. (2023) displayed a monotonic increase for $P \nearrow$ leading

to a local maximum at the maximum pressure $P = 0.60 \text{ MPa}$, the present results appear to plateau, albeit without experimental data for $0.50 \text{ MPa} \leq P \leq 0.60 \text{ MPa}$.

Looking at the effect of θ , there is a gradual reduction in the values of E at any given P , more pronounced for $P \nearrow$ compared to $P \searrow$, and a similar hysteretic behaviour at all tested values of θ . Remarkably, for all values of θ investigated, maxima at $P = 0.05 \text{ MPa}$ for $P \nearrow$ and minima at $P = 0.15 \text{ MPa}$ for $P \searrow$ are evidenced. This is significant as maxima for $P \nearrow$ and minima for $P \searrow$ have previously been shown to vary with muscle density (Marshall et al., 2023), and are now shown to be independent of the orientation. Indeed, the orientation affects the tensile modulus, as the warp best carries tensile load when aligned with the load orientation. The pressure at which the maxima and minima occur mainly depends on the weft and increase or decrease in pressure. Therefore, the orientation governs the tensile response, while the maxima/minima dependent on the pressure and associated deformation of the active textile.

To better understand the effect of θ on E , Figure 11 presents the evolution of the normalised tensile modulus $E/E_{\theta=0^\circ}$ for $0^\circ \leq \theta \leq 30^\circ$. In addition to the clear decline in $E/E_{\theta=0^\circ}$ for increasing θ , associated with the misalignment of the warp with the direction of the tensile loading, there is also an increasing variability in $E/E_{\theta=0^\circ}$ for increasing θ . These findings are particularly relevant to quantifying the loss in tensile modulus associated with a deviation from the load orientation or intended operating angle for active textiles in tension.

The variations in tensile properties of active textiles can, therefore, be quantified as a function of their rotation angle. While the warp provides tensile properties, flexural properties originate from the weft for non-zero pressures. Consequently, it may be hypothesised that maximum flexural properties occur at $\theta = 90^\circ$.

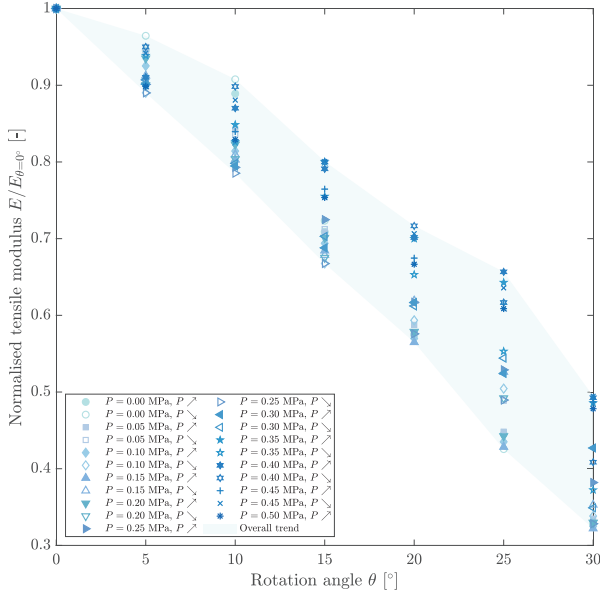


Figure 11. Normalised tensile modulus $E/E_{\theta=0^\circ}$ of the T₁ woven active textile versus rotation angle θ for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$. Error bars omitted for clarity.

Flexural properties. The effect of θ on E_f is presented for $0^\circ \leq \theta \leq 90^\circ$ in Figure 12. While error bars are omitted in Figure 12 for clarity, it is noted that flexural results are subject to a much higher average uncertainty $\bar{U}$ than tensile results (where $\bar{U} \approx 0.06$), particularly at low P and low θ , owing to the very low forces measured. The average uncertainty $\bar{U} \approx 0.40$ for the present flexural results is consistent with that of Marshall et al. (2023), namely $\bar{U} \approx 0.60$ for $0.00 \text{ MPa} \leq P \leq 0.60 \text{ MPa}$ at $\theta = 0^\circ$.

There is a good agreement between present results and those of Marshall et al. (2023) at $\theta = 0^\circ$, showing only a marginal increase in E_f with P , less than the uncertainty. This is explained by the inability of the weft to contribute to the flexural properties at $\theta = 0^\circ$, where flexural properties are driven by the warp, which does not possess meaningful flexural properties. However, as θ increases, there is a marked increase in E_f , with a 55-fold increase between $P = 0.00 \text{ MPa}$ and $P = 0.50 \text{ MPa}$ for $\theta = 90^\circ$. Because of the high uncertainty, any hysteretic pattern (e.g. $0.25 \text{ MPa} \leq P \leq 0.45 \text{ MPa}$ at $\theta = 90^\circ$) is not deemed relevant. In fact, considering the magnitude of the uncertainty, there is no clear hysteretic behaviour shown for flexural properties at any tested orientation, which is consistent with the findings of Marshall et al. (2023) at $\theta = 0^\circ$.

By plotting the normalised flexural modulus $E_f/E_{f,\theta=0^\circ}$ versus θ in Figure 13, two main findings are revealed. First, flexural properties begin to meaningfully increase from $\theta > 15^\circ$, with variations smaller than the magnitude of the uncertainty for $0^\circ \leq \theta \leq 15^\circ$. Secondly, there is a greater rate of increase of

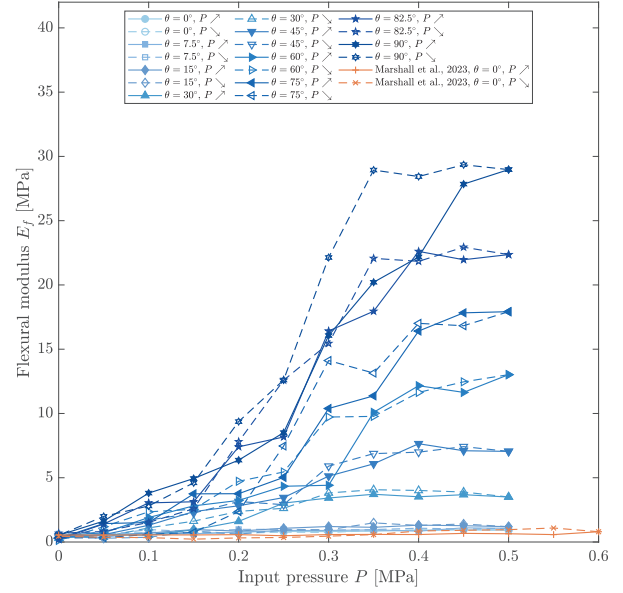


Figure 12. Flexural modulus E_f of the woven active textile ($L_0 = 200 \text{ mm}$, $b = 200 \text{ mm}$) for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$ compared to data from Marshall et al. (2023) ($L_0 = 200 \text{ mm}$, $b = 50 \text{ mm}$) at $\theta = 0^\circ$. Error bars omitted for clarity.

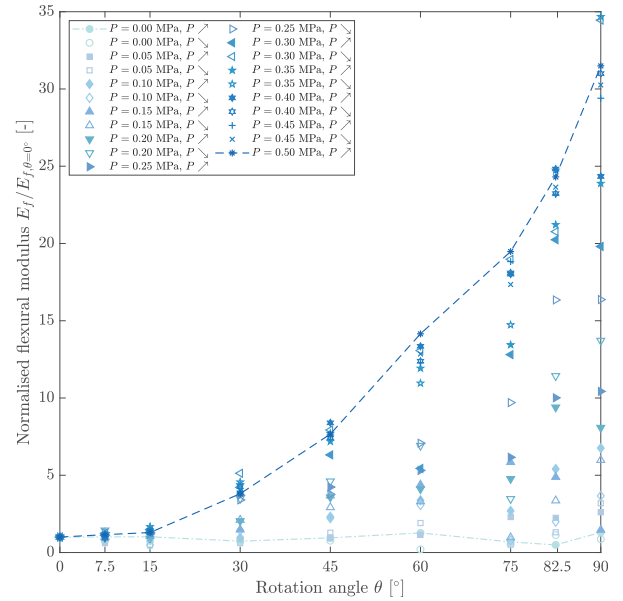


Figure 13. Normalised flexural modulus $E_f/E_{f,\theta=0^\circ}$ versus rotation angle θ for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$. Error bars omitted for clarity.

$E_f/E_{f,\theta=0^\circ}$ for higher values of P . Active textiles can, therefore, exhibit significant flexural properties, as demonstrated in this section, particularly for $\theta > 15^\circ$ and high input pressures. The latter is also associated with an increase in the thickness of the active textile (Figure 8). This contributes to an increase in the second moment of area about the neutral axis $I = bh^3/12$,

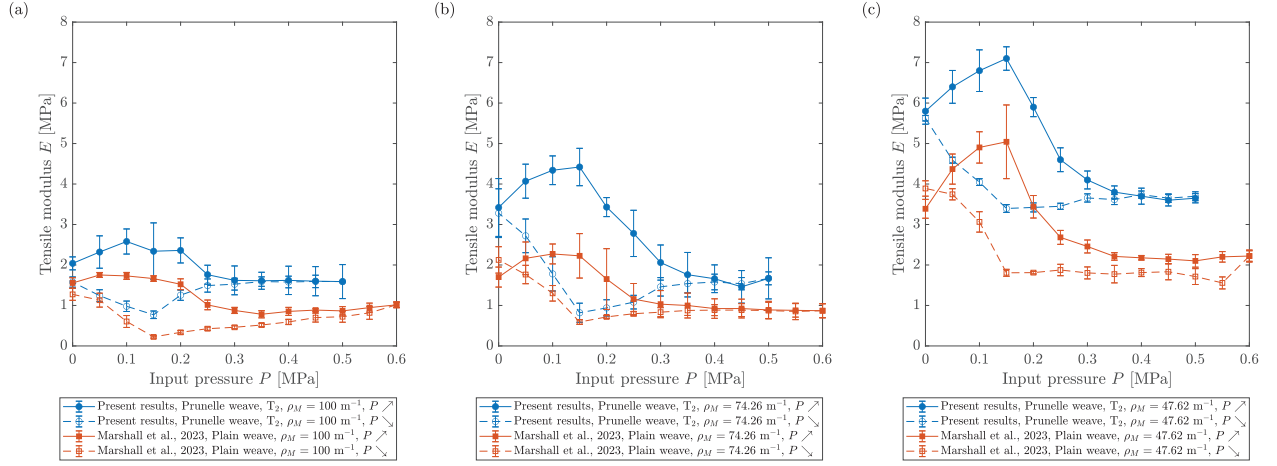


Figure 14. Tensile modulus E of the T_2 active textile versus input pressure for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$ compared to Marshall et al. (2023) at (a) $\rho_M = 100 \text{ m}^{-1}$, (b) $\rho_M = 74.26 \text{ m}^{-1}$, and (c) $\rho_M = 47.62 \text{ m}^{-1}$.

meaning that the flexural rigidity $E_f I$ of the active textile, combining both its mechanical and geometrical properties, would be even greater.

Effect of weave pattern

Because we have demonstrated the impact of load orientation on active textiles, this section solely investigates textile T_2 (200 mm length by 50 mm width). The aim is to understand the effect of the weave pattern, namely a prunelle weave (2 by 1 twill) compared to a plain one.

Tensile properties. The tensile modulus for the prunelle weave at $\rho_M = 100 \text{ m}^{-1}$, $\rho_M = 74.26 \text{ m}^{-1}$, and $\rho_M = 47.62 \text{ m}^{-1}$ is presented in Figure 14(a) to (c), respectively. Results are presented for both increasing ($P \nearrow$) and decreasing ($P \searrow$) pressure, owing to the previously evidenced hysteretic behaviour in tension.

First, for all tested muscle densities, the prunelle weave exhibits higher mechanical properties than the plain weave. Remembering that the prunelle weave results in less deviation from straightness of the warp, and that tensile properties are governed by the warp, this observation is a logical outcome. This also explains the higher modulus, for both prunelle and plain weaves, as the muscle density decreases: the lesser number of weft woven into the warp means that the latter is more aligned with the tensile load, and thus exhibits higher properties. The increase in modulus thanks to the prunelle weave ranges from 31% to 58% at $P = 0.00 \text{ MPa}$ and 74%–91% at $P = 0.50 \text{ MPa}$ for the tested muscle densities. The weave pattern does, therefore, meaningfully affect the active textile's properties at $\theta = 0^\circ$, with minimal deviation from straightness of the warp being associated with a greater tensile modulus. This can be achieved with the weave pattern, but also the muscle

density, both significant design variables, the effect of which will next be ascertained in flexion.

Flexural properties. In flexion, both the present results and literature (Marshall et al., 2023) have evidenced the absence of any hysteresis. Consequently, experiments are performed for increasing pressure only. However, while the plain weave (denoted —) only yields in-plane motion, the prunelle one results in out-of-plane curvature. This geometrical property significantly affects the mechanical properties. Therefore, the prunelle weave is tested both with its concave side upwards ($\cup$) and downwards ($\cap$), as depicted in Figure 15(a) to (c) for $\rho_M = 100 \text{ m}^{-1}$, $\rho_M = 74.26 \text{ m}^{-1}$, and $\rho_M = 47.62 \text{ m}^{-1}$, respectively.

The flexural results retain a high uncertainty, solely driven by the force bias, owing to the very small forces measured. Indeed, as the active textile is not best employed in flexion, very small forces are required to generate large deformation, and thus the comparatively high force bias yields high uncertainty. This was also identified by Marshall et al. (2023). Nevertheless, the differences between prunelle and plain weaves exceed the uncertainty. As such, we can conclude that the prunelle weave appears to offer a higher flexural modulus than the plain weave. More significantly, we identify a drastic change in behaviour between samples tested with their concave side upwards ($\cup$) or downwards ($\cap$). Indeed, the former ($\cup$) displays a reduction in flexural modulus despite an increasing pressure as a result of the out-of-plane curvature not working in favour of withstanding flexural loads. Conversely, when the concave side faces downwards ($\cap$), the curvature created for increasing pressure works in favour of the active textile, allowing the textile to achieve increasing flexural modulus with increasing pressure, at a marginally higher rate than the plain weave (—). Therefore, where

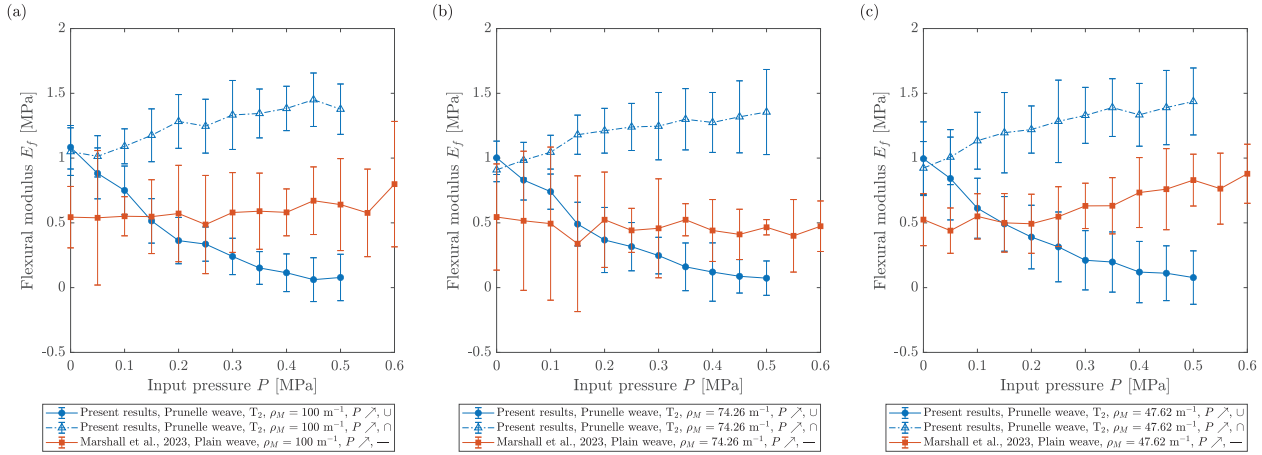


Figure 15. Flexural modulus E_f of the T_2 active textile versus input pressure for $0.00 \text{ MPa} \leq P \leq 0.50 \text{ MPa}$ compared to Marshall et al. (2023) at (a) $\rho_M = 100 \text{ m}^{-1}$, (b) $\rho_M = 74.26 \text{ m}^{-1}$, and (c) $\rho_M = 47.62 \text{ m}^{-1}$.

out-of-plane curvature occurs, the geometrical variations have been shown to play a significant role on the flexural properties. This behaviour will be accentuated by the amount of curvature, which has been shown to vary with both weave pattern and warp material (Hiramitsu et al., 2023).

Conclusions

In this work, the mechanical properties of plain and prunelle (2 by 1 twill) woven active textiles composed of a Nylon 6 warp and EM20 S-muscle weft at muscle densities from 100 m^{-1} to 47.62 m^{-1} were investigated. Experiments were conducted for monotonically increasing and monotonically decreasing pressures from 0.00 MPa to 0.50 MPa while complying with the relevant ISO standards for tensile and flexural testing. As such, new insights into the mechanical properties of woven active textiles can be gained, particularly regarding the effect of load orientation, investigated from 0° to 30° in tension, and from 0° to 90° in flexion, as well as weave patterns.

Firstly, the behaviour of the thin McKibben muscles and two active textiles presented in this work were described. The results showed a clear hysteretic behaviour, as well as the effect of the interference and friction between the warp and weft, which led to higher uncertainty for monotonically decreasing pressures. This is significant as it would affect the response of active textiles under duty cycles.

Secondly, the effect of orientation is tackled. Tensile properties were shown to be strongly impacted by the rotation angle, with a reduction in tensile modulus for increasing rotation angle as a result of the warp no longer aligning with the tensile load direction. Remarkably, irrespective of the rotation angle, the maxima for monotonically increasing pressures were always at 0.05 MPa and the minima for monotonically

decreasing pressures always occurred at 0.15 MPa . For flexural properties, an increase in orientation angle yielded a significant increase in flexural properties, up to a modulus circa 30 MPa at 90° for the highest tested pressures: a 31-fold increase compared to 0° , while a 55-fold increase was achieved at an angle of 90° between pressures of 0.00 and 0.50 MPa . This is consistent with the weft providing the flexural properties of active textiles, with a greater rate of increase of the flexural modulus for rotation angles in excess of 15° . Furthermore, while textile deformation and tensile properties displayed a strong hysteretic behaviour, flexural properties did not, ensuring symmetrical response under duty cycles.

Thirdly, the effect of the weave pattern was studied by comparing a prunelle and plain weave. In tension, a better tensile modulus is achieved by minimising the deviation from straightness of the fibres, which can be achieved either by employing a prunelle weave, or reducing the muscle density, thus allowing to achieve maximum mechanical properties. In flexion, the out-of-plane curvature was shown to yield radically different behaviour depending on the orientation of the curvature. Where the concave side faces upwards, a reduction in flexural modulus was exhibited. Conversely, by orienting the concave side downwards, an increase in flexural modulus was evidenced, with both a greater value and a higher rate of increase than a plain weave.

These findings provide novel insights into the mechanical properties of woven active textiles at rotation angles and for different weave patterns, thereby supporting the prediction of their properties for soft robotic applications ranging from wearable technologies to biomimicry. Specifically, the present results enable safe and comfortable human-centric wearables for complex, multi-degree-of-freedom applications. Indeed, knowledge of the tensile modulus for varying orientations will allow to ensure suitable strength even

when the load deviates from the fibre alignment for applications such as exosuits or wearable joint supports. Where bending is required, the novel insights gained can inform decisions, ranging from weave pattern to muscle density in order to achieve the expected mechanical response, whilst also not causing injury.

However, these properties remain experimentally characterised. As such, they provide crucial validation data for theoretical models, allowing the prediction of the mechanical properties of woven active textiles. Such theoretical models, which remain lacking, may be informed by composite theory, which may, therefore, represent a relevant future research direction.

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Data available on request from the authors.

References

- Abel J, Luntz J and Brei D (2013) Hierarchical architecture of active knits. *Smart Materials and Structures* 22: 125001.
- Andreasson R, Alenljung B, Billing E, et al. (2018) Affective touch in human–robot interaction: Conveying emotion to the Nao robot. *International Journal of Social Robotics* 10: 473–491.
- Castano LM and Flatau AB (2014) Smart fabric sensors and e-textile technologies: a review. *Smart Materials and Structures* 23: 053001.
- Chen J, He T, Du Z, et al. (2023) Review of textile-based wearable electronics: From the structure of the multi-level hierarchy textiles. *Nano Energy* 117: 108898.
- Chen Y, Yang Y, Li M, et al. (2021) Wearable actuators: An overview. *Textiles* 1: 283–321.
- Christensen S, Rafique S and Bai S (2021) Design of a powered full-body exoskeleton for physical assistance of elderly people. *International Journal of Advanced Robotic Systems* 18(6): 1–15.
- Diteesawat RS, Hoh S, Pulvirenti E, et al. (2022) A soft fabric-based shrink-to-fit pneumatic sleeve for comfortable limb assistance. In: *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp.9766–9773. IEEE.
- Eschen K, Granberry R and Abel J (2020) Guidelines on the design, characterization, and operation of shape memory alloy knitted actuators. *Smart Materials and Structures* 29: 035036.
- Garriga-Casanovas A, Hiramitsu TY, Baena FR, et al. (2017) Multifilament pneumatic artificial muscles to mimic the human neck. In: *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pp.809–816. IEEE.
- Greig J, McInnes M, Chadwick EK, et al. (2025) Decoupled, wearable soft robotic rehabilitation device for the upper limb. *Wearable Technologies* 6: e38, pp.1–19.
- Hiramitsu T, Suzumori K, Nabae H, et al. (2019) Experimental evaluation of textile mechanisms made of artificial muscles. In: *2nd IEEE International Conference on Soft Robotics (RoboSoft)*, pp.1–6. IEEE.
- Hiramitsu T, Suzumori K, Nabae H, et al. (2023) Active textile: Woven-cloth-like mechanisms consist of thin McKibben actuators. *Advanced Robotics* 37(7): 480–494.
- Hocking EG and Wereley NM (2013) Analysis of nonlinear elastic behavior in miniature pneumatic artificial muscles. *Smart Materials and Structures* 22: 014016.
- Hu J, Meng H, Li G, et al. (2012) A review of stimulative responsive polymers for smart textile applications. *Smart Materials and Structures* 21: 053001.
- International Organization for Standardization (2012) *ISO 527-2:2012 Plastics - Determination of Tensile Properties - Part 2: Test Conditions for Moulding and Extrusion Plastics*. International Organization for Standardization.
- International Organization for Standardization (2013) *ISO 13934-1:2013 Textiles - Tensile Properties of Fabrics - Part 1: Determination of Maximum Force and Elongation at Maximum Force Using the Strip Method*. International Organization for Standardization.
- International Organization for Standardization (2019) *ISO 178:2019 Plastics - Determination of Flexural Properties*. International Organization for Standardization.
- Kobayashi R, Nabae H, Mao Z, et al. (2024) Enhancement of thin McKibben muscle durability under repetitive actuation in a bent state. *IEEE Robotics and Automation Letters* 9(11): 9685–9692.
- Koizumi S, Kurumaya S, Nabae H, et al. (2018) Braiding thin McKibben muscles to enhance their contracting abilities. *IEEE Robotics and Automation Letters* 3(4): 3240–3246.
- Kurumaya S, Nabae H, Endo G, et al. (2017) Design of thin McKibben muscle and multifilament structure. *Sensors and Actuators A: Physical* 261: 66–74.
- Li J, Meng X, Shen Y, et al. (2024) Design strategy of porous elastomer substrate and encapsulation for inorganic stretchable electronics. *International Journal of Smart and Nano Materials* 15(2): 330–347.
- Marshall R, Soupeez JBRG, Khan M, et al. (2023) Mechanical characterisation of woven pneumatic active textile. *IEEE Robotics and Automation Letters* 8(5): 2804–2811.

- Mirvakili SM and Hunter IW (2018) Artificial muscles: Mechanisms, applications, and challenges. *Advanced Materials* 30(6): 1704407.
- Mun S, Yun S, Nam S, et al. (2018) Electro-active polymer based soft tactile interface for wearable devices. *IEEE Transactions on Haptics* 11: 15–21.
- Na G, Nabae H and Suzumori K (2023) Braided thin McKibben muscles for musculoskeletal robots. *Sensors and Actuators A: Physical* 357: 114381.
- Niikura A, Nabae H, Endo G, et al. (2022) Giraffe neck robot: First step toward a powerful and flexible robot prototyping based on giraffe anatomy. *IEEE Robotics and Automation Letters* 7(2): 3539–3546.
- Pagoli A, Chapelle F, Corrales-Ramon JA, et al. (2022) Review of soft fluidic actuators: Classification and materials modeling analysis. *Smart Materials and Structures* 31: 013001.
- Pulvirenti E, Diteesawat RS, Hauser H, et al. (2022) Towards a soft exosuit for hypogravity adaptation: Design and control of lightweight bubble artificial muscles. In: *2022 IEEE 5th International Conference on Soft Robotics*, pp.651–656. IEEE.
- Salahuddin B, Warren H and Spinks GM (2021) A comprehensive test method for measuring actuation performance of McKibben artificial muscles. *Smart Materials and Structures* 30: 045016.
- Souppiez JBRG and Laci J (2022) Ultimate strength of quasi-isotropic composites: ISO 12215-5:2019 validation. *The Royal Institution of Naval Architects Part A: International Journal of Marine Engineering* 162(A): 237–246.
- Stoppa M and Chiolerio A (2014) Wearable electronics and smart textiles: A critical review. *Sensors* 14(7): 11957–11992.
- Talukder A and Jo J (2025) Elastic textile-based wearable modulation of musculoskeletal load: A comprehensive review of passive exosuits and resistance clothing. *Wearable Technologies* 6: e11.
- Ten Bhömer M, Tomico O and Wensveen S (2016) Designing ultra-personalised embodied smart textile services for well-being. In: Van Langenhove L (ed.) *Advances in Smart Medical Textiles: Treatments and Health Monitoring*. Cambridge: Woodhead Publishing, pp.155–175.
- Thalman C and Artemiadis P (2020) A review of soft wearable robots that provide active assistance: Trends, common actuation methods, fabrication, and applications. *Wearable Technologies* 1: e3.
- Thalman CM, Hertzell T, Debeurre M, et al. (2022) Multi-degrees-of-freedom soft robotic ankle-foot orthosis for gait assistance and variable ankle support. *Wearable Technologies* 3: e18.
- Ueda D, Suzumori K, Nabae H, et al. (2025) Soft robotic heart formed with a myocardial band for cardiac functions. *Soft Robotics* 12(4): 488–497.
- Vraitch R, Ma X, Giorgio-Serchi F, et al. (2024) Additive manufacturing of patient-specific intervertebral disc models for spinal cord compression management. In: *International Conference on Smart and Advanced Manufacturing*, 2024.
- Wirekoh J and Park YL (2017) Design of flat pneumatic artificial muscles. *Smart Materials and Structures* 26: 035009.
- Xiong J, Chen J and Lee PS (2021) Functional fibers and fabrics for soft robotics, wearables, and human-robot interface. *Advanced Materials* 33: 2002640.
- Xu Q, Ying C, Zhang K, et al. (2024) An effective nonlinear dynamic formulation to analyze grasping capability of soft pneumatic robotic gripper. *International Journal of Smart and Nano Materials* 15(3): 405–431.
- Younes R, Hines K, Forsyth J, et al. (2016) The design of smart garments for motion capture and activity classification. In: Koncar V (ed.) *Smart Textiles and Their Applications*. Duxford: Woodhead Publishing, pp.627–655.
- Zhu M, Do TN, Hawkes E, et al. (2020) Fluidic fabric muscle sheets for wearable and soft robotics. *Soft Robotics* 7(2): 179–197.