KnitSkin: Machine-Knitted Scaled Skin for Locomotion

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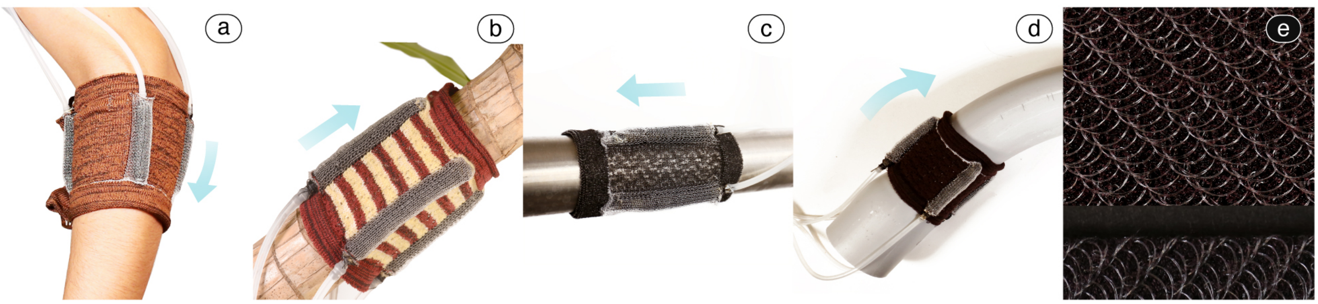

Figure 1: KnitSkin is a bio-inspired sleeve that can traverse diverse cylindrical terrains, ranging from (a) a user's forearm at the wearable scale, to (b) tree branches and (c), (d) pipes at the environmental scale. (e) Python inspired scales are machine knitted on the inside of the substrate to provide elongation for propulsion.

ABSTRACT

We present KnitSkin, a bio-inspired sleeve that can traverse diverse cylindrical terrains, ranging from a user's forearm at a wearable scale, to pipes and tree branches at an environmental scale. Fabricated with a machine knitted substrate, the sleeve configures a stepped array of knitted scales that exhibit anisotropic friction. Coupled with the extension of actuators enclosed in the sleeve, the scales enable effective directional locomotion on cylindrical surfaces with varying slopes, textures, and curvatures. KnitSkin's substrates are characterized by scales whose geometries and materials can be fine-tuned and channels that can accommodate diverse actuators. We introduce the design elements of KnitSkin in which we characterize a series of substrate parameters and their resulting anisotropic behaviors. In evaluating the locomotion, we examine the variables associated with the surface and actuator characteristics. KnitSkin obtains diverse applications across different scales, including wearable interfaces, industrial pipe-monitoring, to agricultural robots.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Machine Knitting, Smart Textiles, Mobile Robots, Wearable Robots

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1 INTRODUCTION

While interactive devices in Human-Computer Interaction (HCI) have typically been static or fixed in one location, there has been increased interest in *mobile* devices which can change their locations. This includes a range of on-body robots [12–14, 33], which can climb on clothing, as well as locomotion and swarm robots [37, 62] that can travel on flat ground and vertical surfaces. However, little research has investigated mechanisms for climbing on *cylindrical surfaces*. Cylindrical terrains, such as the forearm at the wearable scale to pipes, lamp posts, and tree branches at the environmental scale, are widely situated in our daily lives. Mobile robots that can climb on these various cylindrical terrain have the potential to yield new applications from health rehabilitation, industrial monitoring, to urban and agricultural robots. A prime challenge has been a compliant robot form factor that can conform to the geometry of a cylindrical surface while propelling upward.

We introduce KnitSkin, an entirely soft and coordinated system that can climb up underexplored *cylindrical surfaces.* Embodied in a sleeve, the coordinated locomotion system is composed of pneumatic actuators that dominate propulsion and a conformable substrate that exhibits anisotropic friction via a stepped array of knitted scales. The substrate can integrate a comprehensive range of actuators in a minimally intrusive manner. Taking inspiration from limbless locomotion often seen in earthworms and leeches, the actuators linearly extend to enable global propulsion of the sleeve. The flexible substrate accommodates local elongation of the actuators and translates them into a globally coordinated locomotion. Mimicking the skin of certain limbless terrestrial organisms such as the scale of pythons and "setae" of earthworms, the substrate features tunable attributes such as frictional "scales" to direct movement and bolster propulsion. Particularly prominent in KnitSkin is a simple and universal locomotion strategy: the form factor that lets locomotion defy gravity by providing normal force, yet accommodating dynamic movements. With computationally tunable structures, KnitSkin enjoys the freedom of integrating diverse actuators regardless of mechanism, orientation and shapes. The resulting KnitSkin sleeve can crawl on cylindrical surfaces to passively adapt to terrain variations without active control.

In this paper, we introduce the fabrication and mechanical parameters of the knit substrates. We then evaluate the performance of KnitSkin in which locomotion is expressed as a function of different attributes of the substrate parameters and terrain. Drawing from the results, we present various applications in which KnitSkin is envisioned in a wide range of surfaces serving various purposes. By enabling locomotion using soft textile-based fabrication methods, we present a novel mode of traversal that can extend to the human body, pipes or arboreal environments. Our contributions include:

- We introduce computational knitting and linear extension as a locomotion strategy to generate a sleeve-like soft robot that can traverse an uncharted class of terrain: cylindrical surfaces. Our soft approach is compatible with a variety of terrain attributes: material, slope, and curvature.
- We characterize material and geometric attributes of the knit substrate with regard to anisotropic friction. We evaluate terrain variations as main determinants for locomotion. In evaluating the locomotion, we investigate: (1) the impact of terrain materials, (2) the effect of the number of actuators on locomotion, and (3) the impact of terrain attributes such as slope and curvature on locomotion.
- Building upon the results, we introduce applications of KnitSkin encompassing a variety of scales and surfaces, ranging from the human body, industrial pipes to arboreal environments.

2 BACKGROUND AND RELATED WORK

2.1 Bio-Inspired Locomotion

Locomotion strategies in nature adopt a wide range of mechanical tactics to traverse a variety of extreme spaces. Modeling after nature, attempts in robotics to navigate various uneven surfaces [32, 35, 51, 71] and confined spaces [10, 28] have been enabled by hardware that mimics frogs, geckos, cockroaches, or ivy vines. For instance, frog feet have inspired robotic suction cups [71] which can climb walls while consuming low energy. Gecko's sticky pads have led to the development of adhesive appendages [42] which assist robots to climb vertically and turn at 90 degree surfaces. The body motion and compressibility of cockroaches have been studied in legged robots to mimic rapid locomotion in crevices. Likewise, plants offer inspirations that are unique to their growth-based navigation. For example, vines have inspired a variety of robots that can navigate congested and confined spaces [10, 28, 30, 67, 68]. Nonetheless, designed for on-ground operation, such technologies are not known to be compatible with cylindrical surfaces, and nor have they been evaluated with various terrain attributes. In the limited number of studies that have proposed locomotion strategies for pole-like structures, a series of discrete modules [25] or grippers [36] were among popular methods to enable effective gait patterns. Grippers in particular have proven robust on not only irregular tree trunks [36] but even on an overhanging wall [50]. However, they require rigid mechanical units for actuation. In this work we aim to investigate opportunities for a *soft* locomotion system.

Most relevant to this research is the locomotion in limbless organisms such as snakes, earthworms and caterpillars. Due to the absence of appendages to support dynamic motion, these organisms have evolved to make the best use of skin and muscle. Their skins stretch and shrink synchronously with the muscle movement, which aids or hinders the body to protrude forward. For instance, earthworms present "setae" on their skins which anchors the animal in the soil and prevents backsliding. The same is true for scales in snakes. Taking inspiration from snake scales, Rafsanjani et al. [52] explained how adding a skin of stretchable kirigami could help soft actuators crawl. Kirigami substrates coupled with fiber-reinforced soft actuators allowed the skin to pop up, turning isotropic friction into anisotropic friction. While the stick-slip system was proven effective on rough surfaces where the skin can enhance anchoring, it offers little applicability for the specific terrain that we target in this paper. Likewise, the segmentation of muscle in leeches, inchworms and caterpillars have inspired a range of soft robots [6, 15, 63, 64]. While professed as terrestrial locomotion, few advances in locomotion technology in the robotic field are scalable or applicable to cylindrical terrains. As an exception, Agharese *et al.* [1] developed a vine-inspired robot that wraps around the human arm for haptic feedback. However, the tip-extending strategy is far from the notion of *mobile* interface. Taking inspiration from nature, KnitSkin takes broad attributes of cylindrical terrain into account, laying the groundwork for scalable applications from relocatable wearable interfaces to industrial and agricultural robots.

2.2 Deformable Fabric-Based Interfaces

Methods to animate fabric-based interfaces have been extensively studied in HCI. Different actuation mechanisms have been developed to stimulate the shape-changing effects, which can be categorized into *structural* and *local* deformation. *Structural deformation* through yarn or fiber has been enabled chiefly by knitting engineered materials into the fabric [31, 55, 56]. Integration of the materials prompts global deformation for applications in garment compression [27], heat insulation [65], or even artistic expression [60]. However, with known demerits of insufficient force, irreversibility, and lack of local tunability, such applications have yet to be used for performing locomotion on the human body.

Local deformation, on the other hand, enjoys a wider variety of mechanisms from SMA, bi-layer, to pneumatics. Inducing shape-change through SMA has been welcomed thanks to the material's compliant and compact form factor. Contrasted with the earlier bracket, the material is now enclosed into local parts of the interface through sewing or couching [8, 43, 73, 74], weaving [61], 3d printing [41] or layering [2]. Some applications encompass specific purposes from donning and doffing assistance [38], meditation [22], hypotension treatment [26] to autistic spectrum therapy [16]. Other applications of SMA serve a range of on-body haptic applications [2, 23, 29, 34, 61] or rather all-around purpose [41]. Despite the prominent uses in creating local transformation, SMA has not been popularized for locomotion due to its lack of sufficient force for propulsion and irreversibility. Alternatively, shape-change of fabrics can also be achieved by stacking materials with dissimilar responsiveness to stimuli. Deformation through such bi-layer compositions enjoys more complaint materials, such as films [70] and polymer composites [54]. Transformation takes place as the differential of responsive and inert materials modulates expansion and contraction. While shape change through bi-morph has proven to be rapid and precise, it has not been adopted for locomotion applications due to insufficient force and slow recovery. Overcoming the lack of force and slow actuation cycle, more controlled shape change is yielded by combining pneumatics and fabrics. In many studies, soft pneumatic actuators that are enfolded by knit fabrics have demonstrated ability to bend, extend, and rotate, which aided precise control hand motion. Resulting applications lent themselves to effective tools for rehabilitation [11, 44–47, 49, 53, 58, 59]. Nevertheless, few pneumatic-based applications have sought purposes beyond rehabilitation. While serving a different purpose from KnitSkin, the versatile use of knits in conjunction with soft pneumatics inspires our investigations. The stretchability that is unique to knit textiles and no other fabric structures is an important enabling property for KnitSkin's locomotion. On the whole, an ample history of fabric-based shape change has demonstrated extensive utility and compatibility with various materials. However, despite their ability to embrace diverse materials and actuators, deformable fabrics have yet to be used for locomotion technologies, to which this work aims to contribute.

2.3 Wearable Robots for Locomotion

Wearable robots, which explore an alternative terrain to tabletop surfaces [37, 62], bring locomotion onto the human body. While some robots assist with body-location specific tasks, such as on-body fabrication [9] or kinematic movement [40, 72], others are mobile and able to maneuver on clothes or skin. While early work has been centered on the engineering facets of cloth-climbing robots [7, 24, 39], recent work has also demonstrated HCI applications [12, 13, 33]. Rovables [13] and KINO [33] use magnetic wheels to climb clothes, demonstrating applications from healthcare, remote communication, to fashion expression. While cloth-climbing robots have enabled new interaction possibilities, attempts to move directly on skin remain limited. Epidermal Robots [12] uses a skin-suction mechanism embedded in a legged robot to grasp and move up the skin surface. However, the hardware-centric approach suffers from challenges such as sagging of skin and unreliable cup-skin seal on curved body locations. Designed for the arm, Movelet [14] is a motor-driven bracelet that can move up and down the arm for haptic feedback. However, the weight of the device and reliance on adhesive tape constrain the position of arm.

KnitSkin explores a "soft" approach for locomotion, especially taking advantage of knit substrates which have demonstrated conformability not only to curved and challenging body locations [34], but even to diverse terrains in natural [21] and man-made environments [18, 19].

3 KNITSKIN

The overarching principle of KnitSkin's crawling motion lies in the linear extension-recovery and interfacial friction between the knit substrate and underlying surface (Figure 2). Hence, the performance is jointly determined by the textures of cylindrical surfaces and the attributes of KnitSkin interface. KnitSkin adopts actuators and encloses them in channels to enable local elongation. Leveraging flexibility in the knit substrate, the local extension is in turn transferred globally, elongating the entire KnitSkin structure longitudinally. Here we identify design elements of KnitSkin and their role in delivering coordinated locomotion.

3.1 Producing Knit Substrates for Frictional Anisotropy

The knit substrates are fabricated on a digital v-bed knitting machine, SRY 123 SHIMA SEIKI. The knit substrates play two primary roles in KnitSkin: (1) affording frictional anisotropy and (2) serving as an enclosure for actuators. Anisotropy is a property of having directional dependency. In this paper, we pursue *frictional anisotropy*, which means the knit substrate will produce the least resistance when being pushed towards a certain direction. Frictional anisotropy is also a widespread mechanism behind many natural creatures: snake skin [69], bur-clad plant [5] or hairy legs of insects [5], and other animals [3]. Depending on the direction of movement, angled protrusions slide smoothly or ratchet the contacting surface [20]. To develop frictional anisotropy, we have engineered a novel knit structure that marries yarns with conflicting characteristics of stiffness and elasticity. We also take advantage of the vertical progression of knit in which a row knits first followed by another to form a texture in a stacked manner. KnitSkin's substrate is composed of three features: *a ground layer, scales* and *channels*.

Yarns with elastic properties form the *ground layer* while yarns with high stiffness and less elasticity form the *scales* (Figure 3). The *channels* can be knitted with either of the two yarns. The *ground layer* knits on the needles forming regular knit loops, whereas the *scales* skip the needles, leaving the yarn to run freely across the back of the *ground layer*. The *scales* are knitted row-wise, with the scale tips stacking over the succeeding rows, creating a stepped texture. While knitting on the machine, the *ground* yarn is put

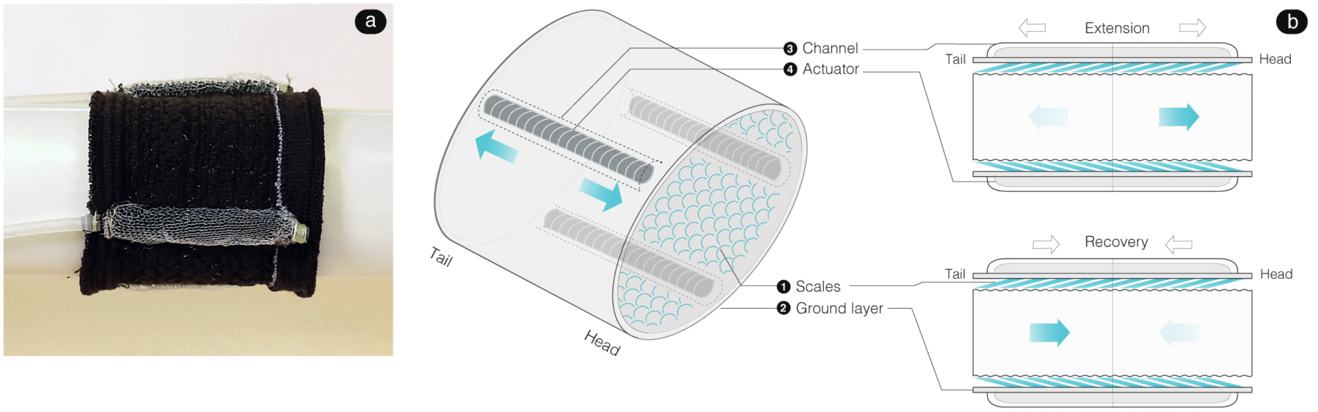

Figure 2: KnitSkin composition. (a) The resulting sleeve, which configures three channels with pleated actuators enclosed. The scales are knitted on the inside. (b) The mechanics of propulsion: during extension, the scales on the side of the head slide forward while the ones on the tail interlock with the surface. During recovery the scales on the tail propel while the ones on the head anchor on the surface.

under tension as it is being stretched to knit on needles that are apart. Once the knit structure is released from the needle bed, the stress built up in the *ground layer* lets the entire structure including the *scales* draw in. This shrinkage is larger along the rows than columns, affecting a great amount of lateral flexing of *scales* (Figure 3(c)). An adequate amount of elasticity in the *ground layer* and the stiffness in the *scales* is crucial, as the balance between them determines the angled orientation of the *scales* (Figure 3 (a), (b)). For instance, if the *scale* yarn exhibits little stiffness as in Figure 3 (b), it is prone to generating scales with a negligible curve. We elaborate on each feature of the substrate below:

- **Scales**: The size, pattern, density and roughness of the *scales* can be tuned with few constraints as long as the elasticity of the *ground layer* and the stiffness of the *scales* strike a good balance. For instance, the size of *scales* can be tuned by letting the *scales* skip more needles (Figure 4 (a)-(c)). By arraying *scales* in straight columns such that no adjacent *scales* are pressing them down one can expect lofty *scales*, whereas by patterning the *scales* so they imbricate one can obtain low-rise *scales* (Figure 4 (d)-(f)). Likewise changes in the density (Figure 4 (g)-(i)) and the roughness of the *scales* can contribute to the anisotropic properties of the substrate. We identify detailed geometric and material parameters of the *scales* and characterize resulting anisotropic effect in later sections.
- **Ground layer**: The role of the *ground* is to withstand a certain amount of stress during knitting. When released from the needle bed, the *ground* pulls in the *scales* laterally. The limited elasticity in *ground* yarns could result in little retraction, which in turn leads to *scales* that are less curved. When the *scales* are straightened up (not curved), they no longer stack onto each other losing the stepped texture. One can dampen the amount of pull-in by combining less elastic yarns with elastic ones or enhance the extent of pull-in by knitting with multiple elastic yarns.
- **Channels**: To enclose a wider variety of actuators, we extend the tubular jacquard structure that has been demonstrated by Kim *et al.* [34]. The structure creates pouches in various shapes and dimensions, however wide or thin. By altering tubular jacquard, substrates can accommodate different numbers of actuators in different shapes. *Channels* can be constructed in conjunction with the scale and ground. A variety of materials outside actuators can be tucked into *channels* through a knitted hole, without additional efforts for integration.

3.2 Producing Actuators for Longitudinal Extension

KnitSkin enables locomotion through longitudinal extension of the sleeve. While the substrates can accommodate a wide range of materials, in this paper we build upon soft pneumatic actuators from past literature, due to their compliance and potential portability [57]. We specifically choose soft pneumatic actuators with pleated sheaths for their relatively high thrust force [66]. The pneumatic actuator consists of off-the-shelf materials: inner tubing (Super-Soft Rubber Tubing for Air and Water, McMaster), pleated sheath (Expandable Sleeving Gauze Polyester Fabric, McMaster) and custom 3D printed fittings. The pleated sheath can be made out of an expandable braided sleeve. To form pleats, the sleeve is compressed axially while expanding radially. Then the sleeve undergoes heat treatment to secure the pleats. The resulting pleated mesh contains the radial expansion of the inner tubing, thus forcing the expansion to translate axially.

To expand the actuators, a compressor is used with a regulated output pressure of 42 psi. The compressor output is fed into the actuators through a 3-way pneumatic solenoid valve. The solenoid valve is fed with 12V pulses to achieve repeated expansion and contraction of the actuators. The solenoid valve is connected to a normally closed configuration. When the solenoid valve is supplied with 12V, the air flows from the compressor to the actuators and

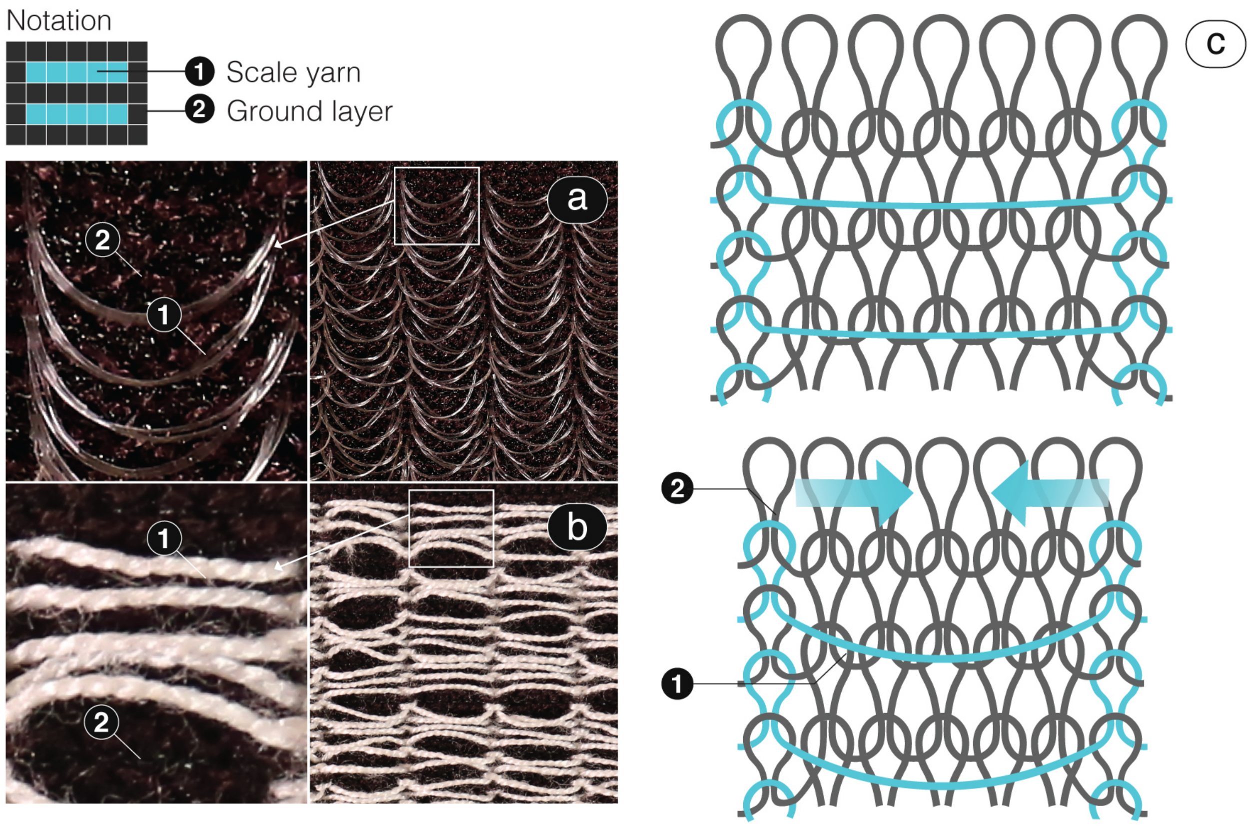

Figure 3: Knit structure to form a scaled substrate. The notation indicates that five needles are skipped to form a scale. (a) Illustrates when the scales consist nylon monofilament. The stiffness of monofilament induces the curve as the ground layer draws in. In contrast, scales in (b) show negligible curves due to the lack of stiffness in the yarn. The scales are straightened up, causing no "stepped" texture. (c) depicts the change in tension as the substrate is released from the needles post-knitting. The draw-in of knit loops induces the lateral curve of the scales.

expands the actuators. When the solenoid valve is supplied with 0V, the air in the actuators is exhausted through the exhaust port of the valve. The time period and the duty cycle of these 12V pulses is controlled using an Arduino controller. The 5V output of the Arduino is fed to a relay which switches the 12V supply to the actuator. A digital pressure gauge is also connected to monitor the pressure in the actuators.

4 KNIT SUBSTRATE PARAMETERS: TUNING FRICTIONAL ANISOTROPY FOR LOCOMOTION

One way to achieve frictional anisotrophy is to shape the surface with an array of angled *protuberances*. A protuberance is an obstacle on a surface, sometimes referred as bumps or hairs [20]. Filippov *et al.* [20] studied how protuberances can cause different frictions in different directions. The scales in the KnitSkin can be seen as an array of protuberances. These protuberances have angles because the scale tips stack over the scales on the succeeding rows, as illustrated in Figure 2 (b).

Tuning granular details of the *scale* to examine their impact on the friction can be most effectively achieved by altering the parameters below. Here we lay out how the *scales* are formed on the knitting machine, and how the two primary determinants - scale *geometry* and *material* - influence the anisotropy of friction. While the two parameters complement each other, we focus on how geometrical parameters induce global effects across the fabric while material parameters dominate the behavior of an individual scale. All geometrical parameters presented below are based on a 5-stitch unit, except for the scale length parameter.

4.1 Scale Geometry Parameters

- *Scale length*: The *size* of a scale is determined by the number of needles skipped between two ends of a scale. When a yarn skips a needle, it runs across the back of the fabric instead of forming a knit loop. The free strand of the yarn forms a downward arch once the ground fabric is released from the needle bed. The *scale lengths* tested in this paper are 2, 5, and 11 stitches, shown in Figure 4 (a)(b)(c). Note 2-stitch is the smallest possible length in order for scales to curve.

- *Global pattern*: The *pattern* of scales influences the behavior of the substrate. In the knitting process, the scales are knitted row by row. This process controls how scales are stacked and which part of a scale is weighed down. When scales are stacked, the tendency to roll back diminishes as the adjacent scales are pressing down on them. For instance, in the zigzag pattern (Figure 4 (e)), each scale is stacked under the halves of two scales on the succeeding row, yielding the most balanced configuration. Scales in the diagonal pattern (Figure 4 (d)) leaves the right end of a scale uncompressed by adjacent scales. The wavy pattern results in a less controlled array from the side view (Figure 4 (f)). Note these three patterns have better rollback resistance compared with the column pattern used in Figure 4 (a-c), because the column pattern has the least overlaps among the scales.
- *Density*: The *density* is defined as the distance between two rows with scales. For example, a density of 1 row indicates the scales are knitted every other row. Figure 4 (g), (h), and (i) examine the densities of 1, 2, and 4 rows, respectively. Low density yields low anisotropic friction because it exposes more ground yarns, and the friction from the ground yarns is uniform across all directions.

4.2 Scale Material Parameters

While the geometrical parameters affect the global behavior of the substrate, the yarn material determines the characteristics of the scales. Figure 5 demonstrates scales knitted with different types of materials. Considering the stiffness of the materials and their compatibility with knitting machines, we chose Nylon monofilament, 38 AWG copper wire and silver plated multi-filament (Lumina, 65% viscose, 35% metallized polyester, Silk City) for our experiments.

- *Material roughness*: The surface and cross-section of a material influences the overall roughness of the substrate, which in turn impacts the friction. Single filament materials such as nylon monofilaments and metal wires exhibit smoother surfaces; they have a solid cross-section, often in the shape of a clean circle. On the contrary, multi-material yarns such as silver plated multi-filament consist of a core yarn and a wrapper, displaying a non-uniform cross-section. The bristly surface of multi-material yarns, which are akin to the metal-plated ones, can also be attributed to the incoherent yarn composition. Likewise, staple yarns or spun yarns which are composed of fibers cut to short lengths tend to have a "fluffy" surface texture. However those staple yarns are deemed unsuited for knitting scales as they tend to lack stiffness.
- *Material rigidity*: The *curvature* of scales is closely tied to the capability of the material to store tension during and after the knitting process. We observe that the scale curvature is determined by the two main facets: material *stiffness* and *elasticity*. For instance, while the stiffness of copper wire produces some degree of curvature, the lack of elasticity makes it prone to getting bent permanently without rebound (Figure 5 (b)). Yarns with little stiffness, as well as little elasticity, such as Puma (80% viscose, 20% Elite, Silk City) do not get stressed under knitting, thus straightening out post knit (Figure 3 (b)). Similarly, materials with excessive stiffness (e.g., copper wires thicker than 34 AWG) cannot withstand the stress and are likely to break during knitting.

4.3 Resulting Anisotropic Characteristics

The head-to-tail direction of the scales determines the anisotropy of the substrate; it is expected to experience the most friction with the movement travelling towards the tail, and the least towards the opposite direction. Since scales point to the tail (Figure 2 (b)), we can anticipate it will take the least amount of force to move KnitSkin forward (towards the head direction) and the most force to move it backwards (towards the tail). To quantify the anisotropy, we define the *force ratio* as the force to move KnitSkin forward, over the force to move it backward. The ratio is anticipated to be below 1, and the smaller the ratio, the easier for KnitSkin to move towards one specific direction (i.e., forward.)

To measure the force needed to move the KnitSkin towards these two representative directions on a cylindrical surface, we attach the initial load on one of the two ends, and increment loads until displacement is observed. We first test the *material* parameters (nylon monofilament, 38 AWG copper wire, and silver plated multi-filament (Figure 5)) to identify the most suitable material. We then proceed with the *geometry* parameters, testing the nine options in Figure 4 to identify the most optimal setup. For the scale geometry parameter, we test three representative options for scale length, scale pattern, and scale density. We aim to provide initial characterization of how these individual factors impact the force ratio, instead of an extensive full-factorial characterization. Each setting is tested 5 times to account for variability. Attributes of the cylinder and other experimental set up remain the same across the entire experiment for consistency.

Our data shows that for backward force, namely when the angle of the scales interlocks with the surface, greater force was required regardless of materials (Table 1). Among the materials the nylon monofilament recorded the greatest gap between the head (forward) and tail (backward) directions. 13.6% less force was needed when the slope of scales was positioned forward. While the 38 AWG copper wire similarly produced less force of 11.8%, the silver plated multi-filament recorded the least amount of force gap of 7.2%. Following the results, we chose the nylon monofilament to test the *geometry* parameters. Of the nine geometry variations, the one that yielded the greatest force gap was f (Figure 4). All nine variations indicated greater force for backward displacement. From the box plot showing how these force gaps were distributed throughout trials, we noticed that configuration g and h have contributed to larger interquartile ranges (Figure 6). This indicated that the reduced density of scales may have resulted in less consistent force when pulled forward. We also noticed that the *density* variations overall informed of an insignificant gap of medians, less than 10%, which could be a result from a greater exposure of the ground yarn than *pattern* and *scale length*.

5 LOCOMOTION EVALUATION

In our preliminary characterization we investigated parameters of *scales* and their influence on frictional anisotropy. The objective of this study is to understand the propulsion ability of KnitSkin by deploying it on actual cylindrical terrains. In order for KnitSkin

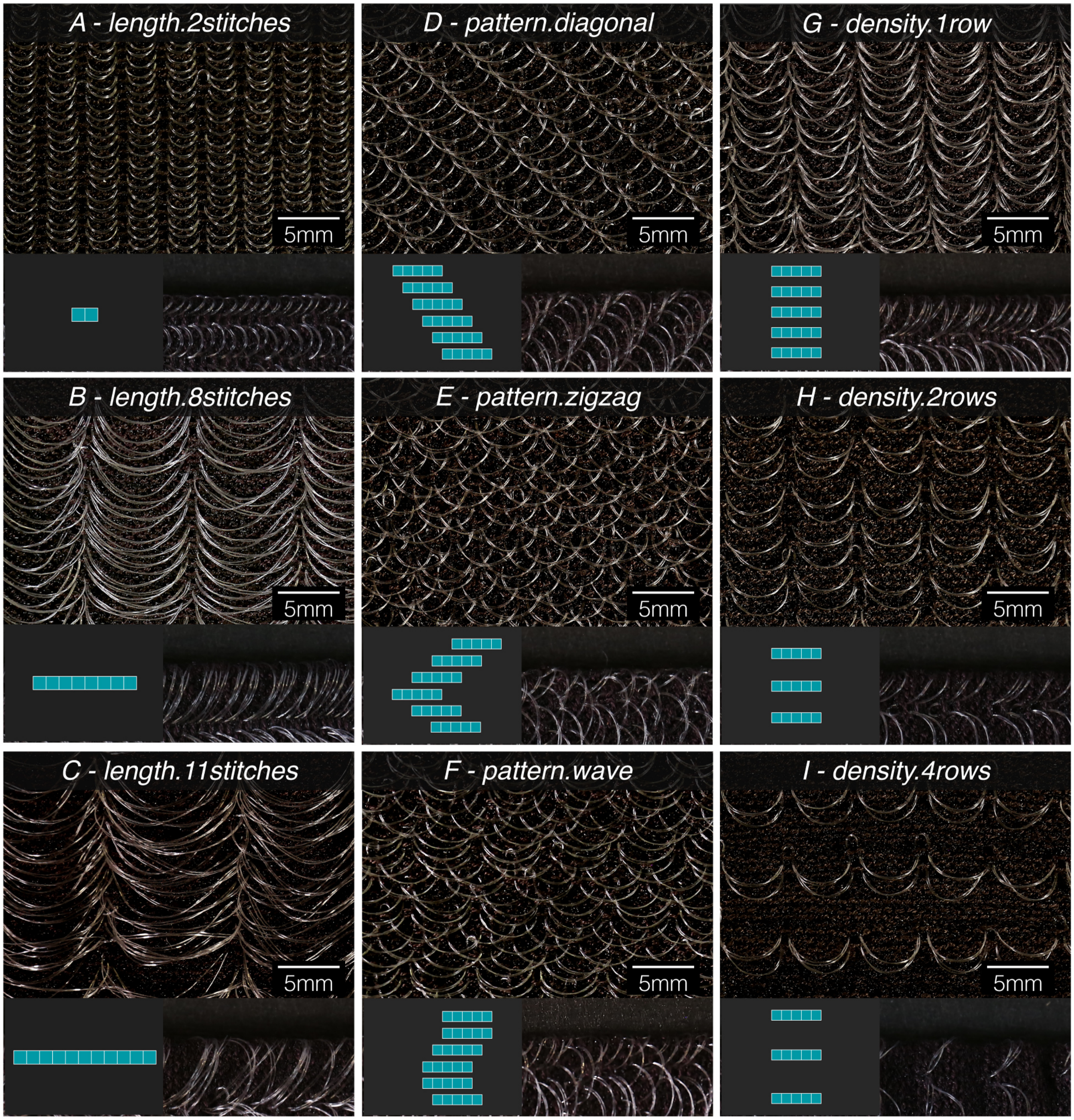

Figure 4: Geometry parameters of scales. The notations on the bottom left corner of the cells denote the numbers and configurations of stitches to form *scales*. The dark background of the notation represents *ground layer*. Presented in each cell are resulting substrates from top and side views.

to serve inter-scale uses it is critical to leverage its design and realize locomotion on a wide subset of cylindrical surfaces. In this evaluation, we focus on how the individual factors below affect the traversal distance. The interaction between the factors is thus not the focus of this investigation. The traversal distance is expressed as the function of actuation cycle while varying: (1) surface materials (2) the number of actuators (3) the slope of terrain, and (3) the curvature of terrain. Unless otherwise specified we manually mark the location of the tail of the interface after each cycle, while recording the process through an external camera. As the duration

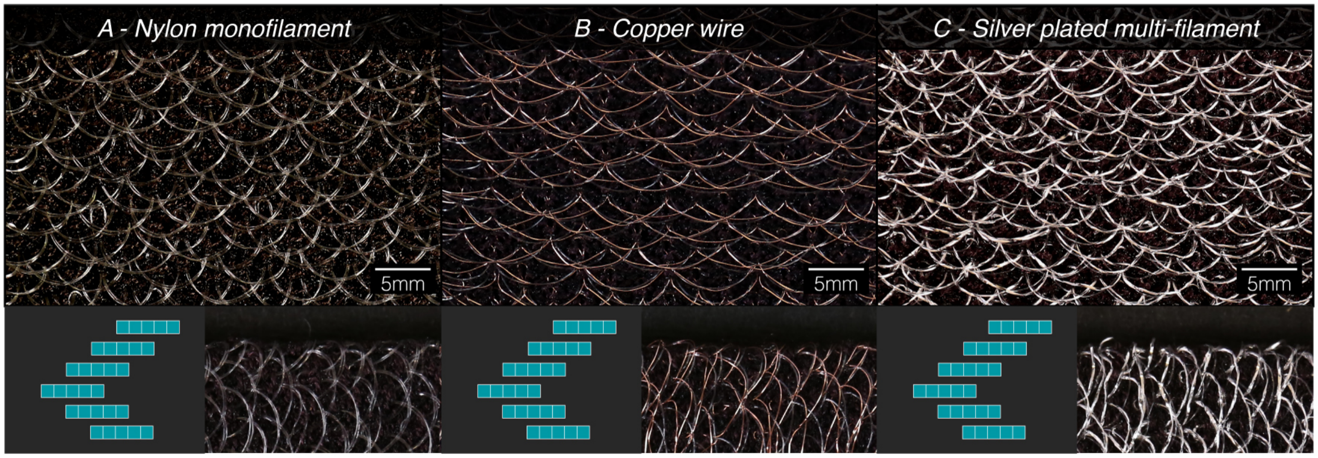

Figure 5: Material parameters of scales. With the same stitch length and pattern, varying materials affects the properties of an individual scale, which in turn affects anisotropic friction.

Table 1: The force ratios of pulling KnitSkin forward over pulling backward under different materials (demonstrated in Figure 5). A smaller ratio indicates that it is easier to move KnitSkin *forward* with the setup.

Material Parameters	Ratio	Material Parameters	Ratio	Material Parameters	Ratio
A - Nylon monofilament	**0.873**	B - 38 AWG copper wire	0.881	C - Silver plated multi-filament	0.927

Table 2: The force ratios of pulling KnitSkin forward over pulling backward under different geometry parameters (demonstrated in Figure 4.) A smaller ratio indicates that it is easier to move KnitSkin *forward* with the setup.

Geometry Parameters	Ratio	Geometry Parameters	Ratio	Geometry Parameters	Ratio
A - length.2stiches	0.917	D - pattern.diagonal	0.911	G - density.1row	0.994
B - length.8stiches	0.889	E - pattern.zigzag	0.768	H - density.2rows	0.918
C - length.11stiches	0.693	**F - pattern.wave**	**0.692**	I - density.4rows	0.997

of exhaust and intake—which comprise one actuation cycle—can be desirably programmed, we take the actuation cycle as a unit for travel speed.

5.1 Surface Materials

The traversal distance is the result of a variety of interfacial properties involving the underlying surface materials and their roughness [20]. In the study we aim to inspect a wide range of materials through which we envision use cases of KnitSkin across various applicable scales.

Procedure and Apparatus. During the test, we use a knitted substrate configured with the knit pattern f from scale parameters (Table 2) and nylon monofilament material, following the results from the anisotropy characterization (Table 1). Three pneumatic actuators are spaced evenly and integrated in the sleeve, with the pressure set at 42 psi. We use the distance that the interface travels in 10 inflation-then-deflation cycles as our evaluation metric. Each cycle involves a 3-second inflation and a 1-second deflation. We repeat this for 10 rounds for each parameter except for terrain curvature. The slope of the surface was set at 180 degrees (parallel to the ground), with a diameter of 2 inches.

The list of surface materials evaluated includes: extruded polyvinyl chloride (PVC), reinforced vinyl, steel, polyurethane laminate (PUL, 75% polyester, 25% polyurethane), silicone rubber, and neoprene. The selected materials cover a wide range of cylindrical surfaces that KnitSkin can climb on: PVC, reinforced vinyl, and steel represent materials widely used in industrial applications; PUL, silicone rubber, and neoprene are known for similar properties to human skin allowing the materials to be widely used to simulate physical properties of the skin [17].

Prior to the evaluation, we use a profilometer (10x, Keyence VK-X260 Laser-Scanning Profilometer) to scan the surface and to measure the roughness (i.e., the characteristics of peaks and valleys on the surface) of each material. The scanned images and the 2-point profiles (i.e., the surface elevation and depression along a straight line) are presented in (Figure 7). As conduits which are extruded during fabrication, PVC and reinforced vinyl tubes present horizontal textures. While both PUL and steel show recognizable

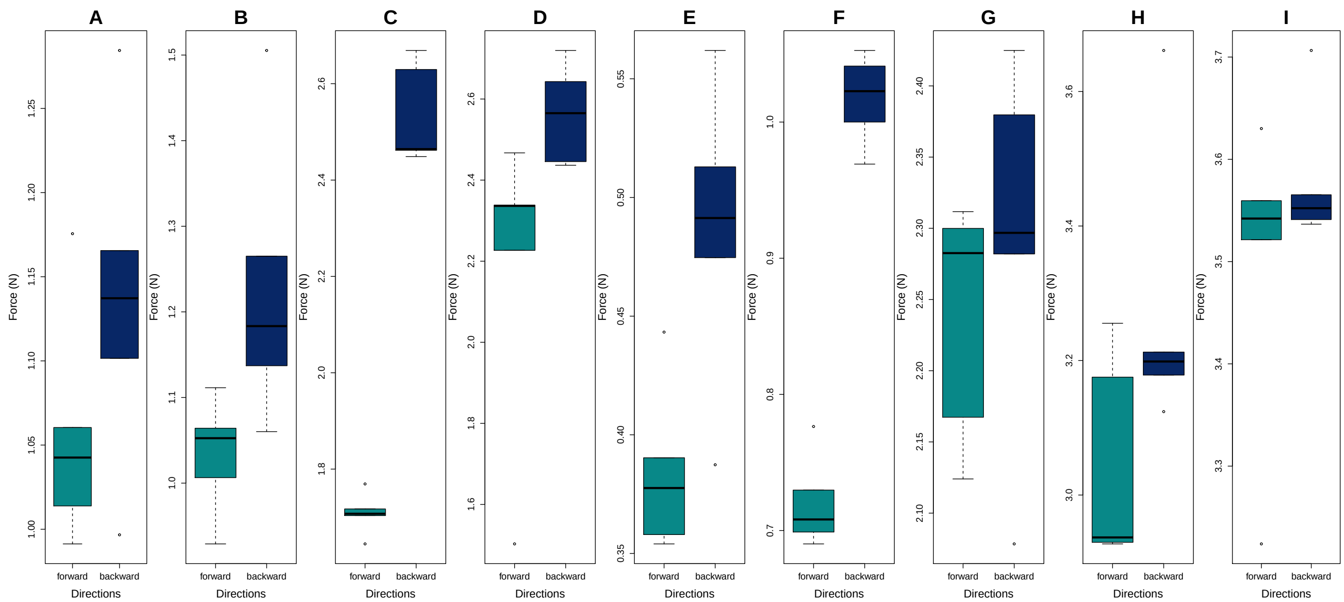

Figure 6: The distribution of force values under geometry parameters. Monofilament scales varied across different scale lengths, global patterns and density. While the medians between the forward and backward directions across *density* show trivial gaps, the medians of all variations indicate greater force required for the backward displacement.

depressions, the ones on PUL span across larger area. Neoprene and silicone rubber indicate relatively shallow and small bumps.

We use *developed inter-facial area ratio* (denoted as *Sdr*) to quantify surface roughness [48]. The ratio is defined as the percentage of the additional surface area contributed by the texture normalized by the area of interest. Thus, a rough material results in a larger value due to the additional area contributed by peaks and valleys.
Results. Materials with larger *Sdr* tended to be conducive to more effective locomotion (Figure 7 (a)). With the exception of silicone rubber, the materials with *Sdr* larger than 0.1 outperformed the rest and helped KnitSkin travel more than 110mm in 10 cycles. The results (Figure 7 (b)) showed that the KnitSkin travelled the farthest distance on the PVC cylinder. While locomotion on the PUL started off by outrunning the performance on the PVC, it started to slow down after 3 cycles.

5.2 Number of Actuators

Procedure and Apparatus. The knitted substrate maintains the pattern f from scale parameters (Table 2) and nylon monofilament material (Table 1). The PVC cylinder with a diameter of 2 inches is placed parallel to the ground. The number of actuators is the only varying factor in this test. The possible configurations are two, three and four actuators. The actuators are spaced evenly apart across the circumference of the substrate. The pressure is set at 42 psi, with a sequence of inflation-then-deflation cycles.
Results. Our results suggested KnitSkin travelled farther when there were more actuators (Figure 8). The three- and four-actuator setup travelled 1.1x and 2.4x compared with the two-actuator case. Through a visual inspection during the test, we found that the four-actuator setup performed much better than the other two because more actuators helped transfer local extension globally. On the contrary, in the two-actuator case, the substrate between the actuators remained static, and the actuators were more prone to buckling. This indicates that if extension was disproportionately concentrated to one or two of the actuators, the local extension would not transfer across the substrate.

5.3 Slope of Terrain

Procedure and Apparatus. The knitted substrate maintains the pattern f from scale parameters (Table 2) and nylon monofilament material (Table 1). Following the results from the previous test, four pneumatic actuators are spaced evenly and integrated in the sleeve, with pressure of 42 psi. We used a PVC surface, tilting the slope from 20, 30 to 40 degrees.
Results. We observed a decrease in the traversal distance when the slope became steeper (Figure 9). In comparison with the 20-degree slope, we observed a 30% and 50% drop in displacement with 30- and 40-degree tilted terrains respectively. The performance degraded considerably when the terrain is tilted beyond 40 degrees.

5.4 Curvature of Terrain

Procedure and Apparatus. To evaluate if the interface can maneuver on a curved cylindrical terrain, we prepare two PVC pipes (i.e., curved cylinders) bent by 45 and 90 degrees, with the same radius of 9.5 inches. The pipes are placed flat, lifted 3 inches from the ground. We place the interface at the tangential extensions before the curve (Figure 10), and test if the interface can crawl and pass the curve. We manually mark the location of the head along the centerline after each cycle, while recording the process through an overhead camera. Similar to prior setups, the interface uses pattern f from

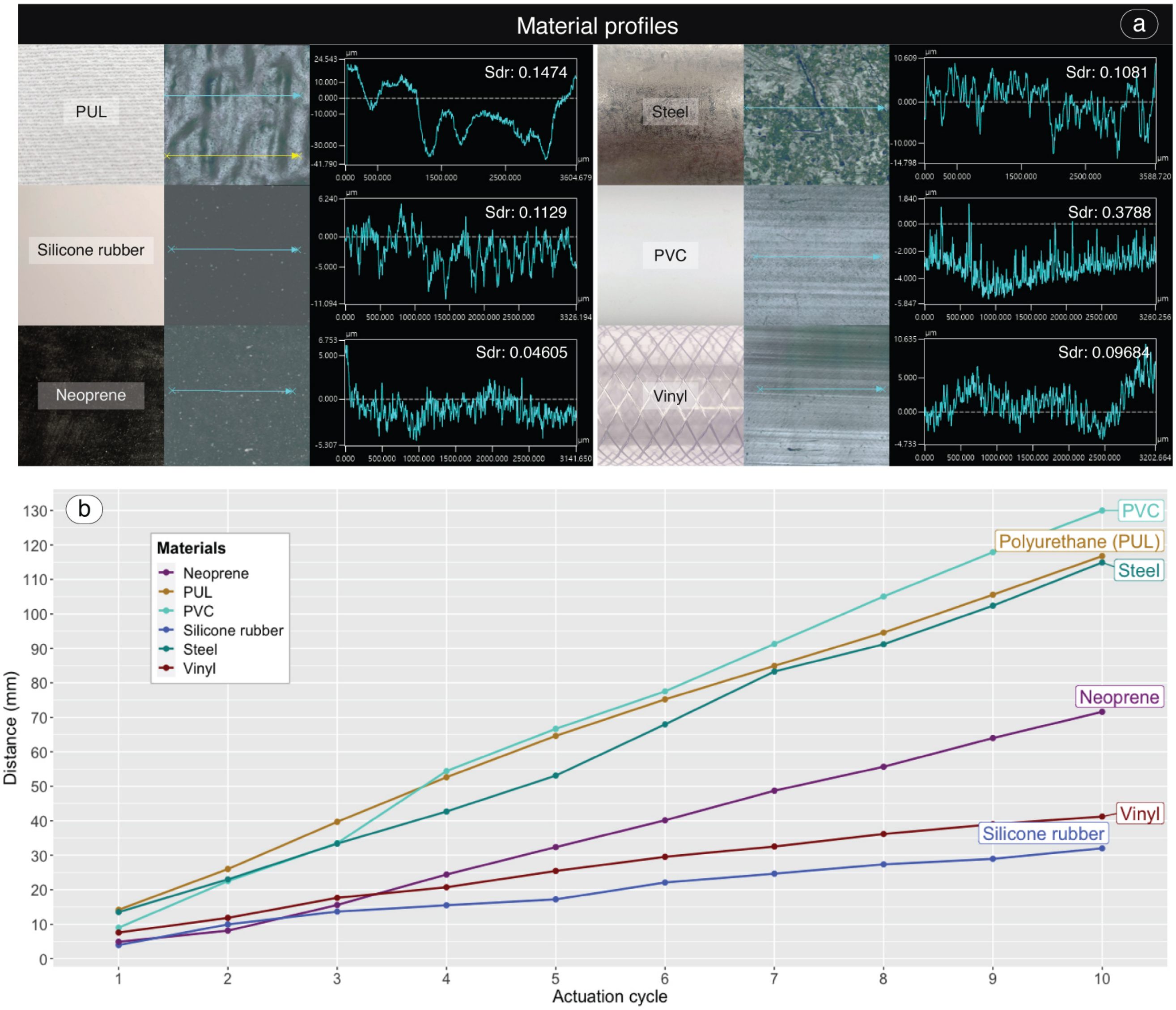

Figure 7: The effect of surface material on travel distance. (a) Demonstrates raw images of surface materials, images of the materials scanned with a profilometer, and 2-points profile from left to right of the arrows. We present values of *Sdr* as a roughness parameter. (b) Presents locomotion distances in millimeter by actuation cycles.

Table 2 and nylon monofilament material (Table 1). Four pneumatic actuators are spaced evenly and integrated in the sleeve. In this test we do not limit the actuation to 10 cycles. Instead, we seek to observe how many cycles would be repeated for the interface to pass the curve and enter the tangent on the other side.

Results. The result is expressed through manual measurement (Figure 10) and as the function of actuation cycle (Figure 11). In both measurements the result indicated that the interface was able to maneuver through the curves. However, the distance travelled per cycle was less consistent compared to the other factors. From the manual measurement, it took 18 cycles for the interface to pass the 90 degrees curve whereas 16 cycles were executed to pass the 45 degrees curve (Figure 10). On the 90 degrees curve the interface maneuvered less from the 4th to 12nd cycles, whereas from the 12nd to 15th cycles, the interface seemed to pick up speed. On the 45 degrees curved terrain, the interface travelled more from the 7th cycle (Figure 11). Outside these two measurements, our visual inspection notified us that when the interface was passing through the curved region of the 90 degrees terrain, the actuator on the inner most arc extended off the cylinder axis; it did not conform to the curvature during actuation but extended along the chord. This created an area where few scales seemed to be in contact with the terrain, which could have driven the sluggish locomotion compared to that on the straight terrains.

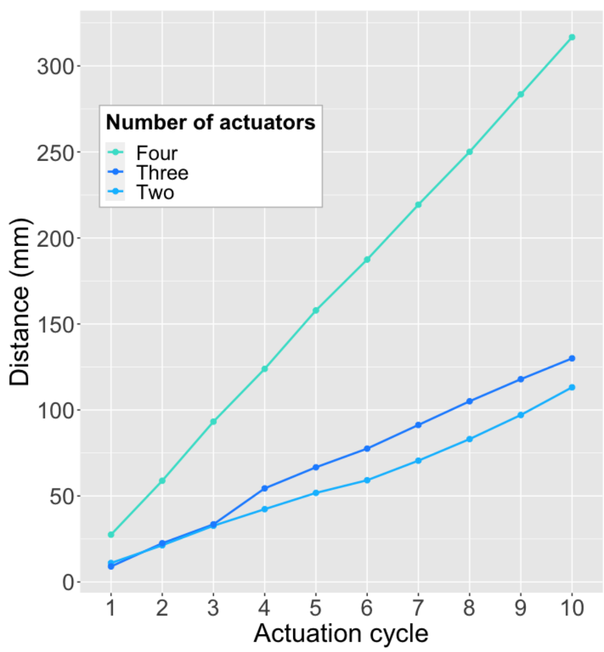

Figure 8: The effect of the actuator number on travel distance.

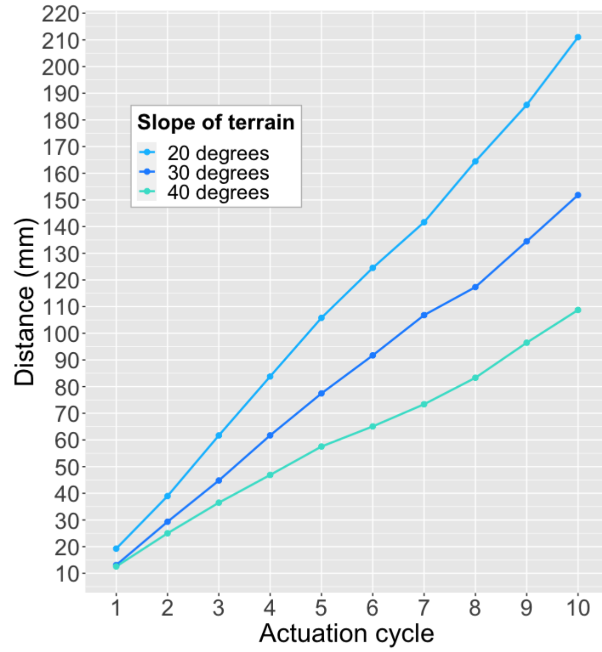

Figure 9: The effect of the slope of terrain on travel distance.

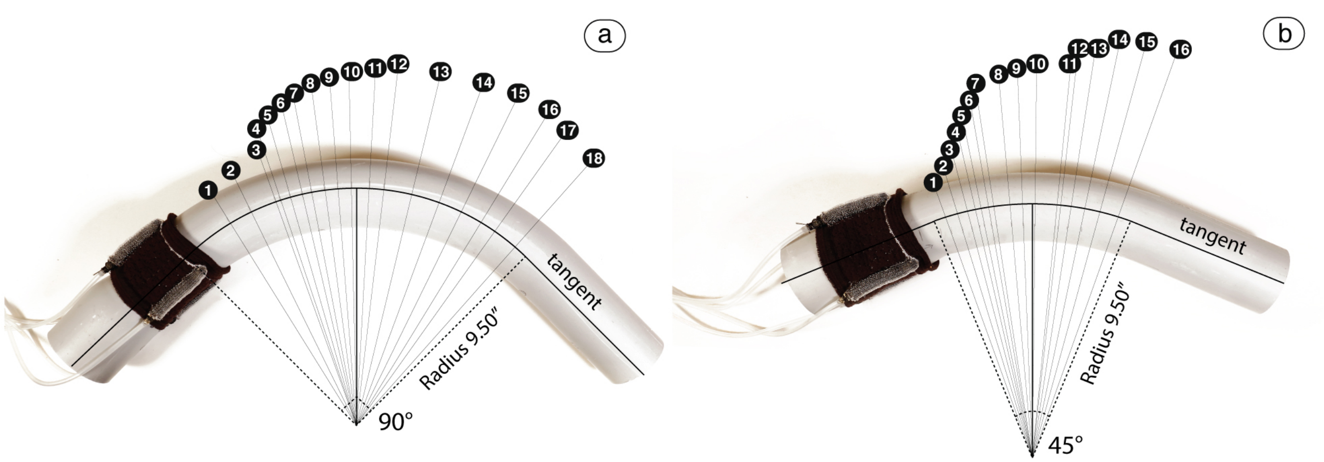

Figure 10: (a), (b) Locomotion on 90 and 45 degrees curved terrain. The numbers denote the progression of locomotion cycles. The intersection between the center line and the corresponding lines is where the substrate concluded a cycle.

6 APPLICATIONS

We demonstrate applications of KnitSkin on various surfaces, from the wearable scale to the industrial and environmental scales. We build on our insights from the evaluation section for selecting our application contexts.

6.1 Wearable and Relocatable Interface

In evaluating a variety of surface materials, we learned that the KnitSkin substrate can crawl on synthetic materials, such as PUL, silicone rubber and neoprene, which share the properties of human skin [17]. Given its soft and knitted form, KnitSkin resembles clothing, making it an appropriate form factor for on-body locomotion. In addition to the form factor, the channels' ability to accommodate a wide range of actuators means it can be altered to create a pocket for input sensors and output feedback modules. Taking advantage of such attributes, we envision a relocatable wearable interface that can change its location for voice input (Figure 12). When the interface receives an incoming call while both of a user's

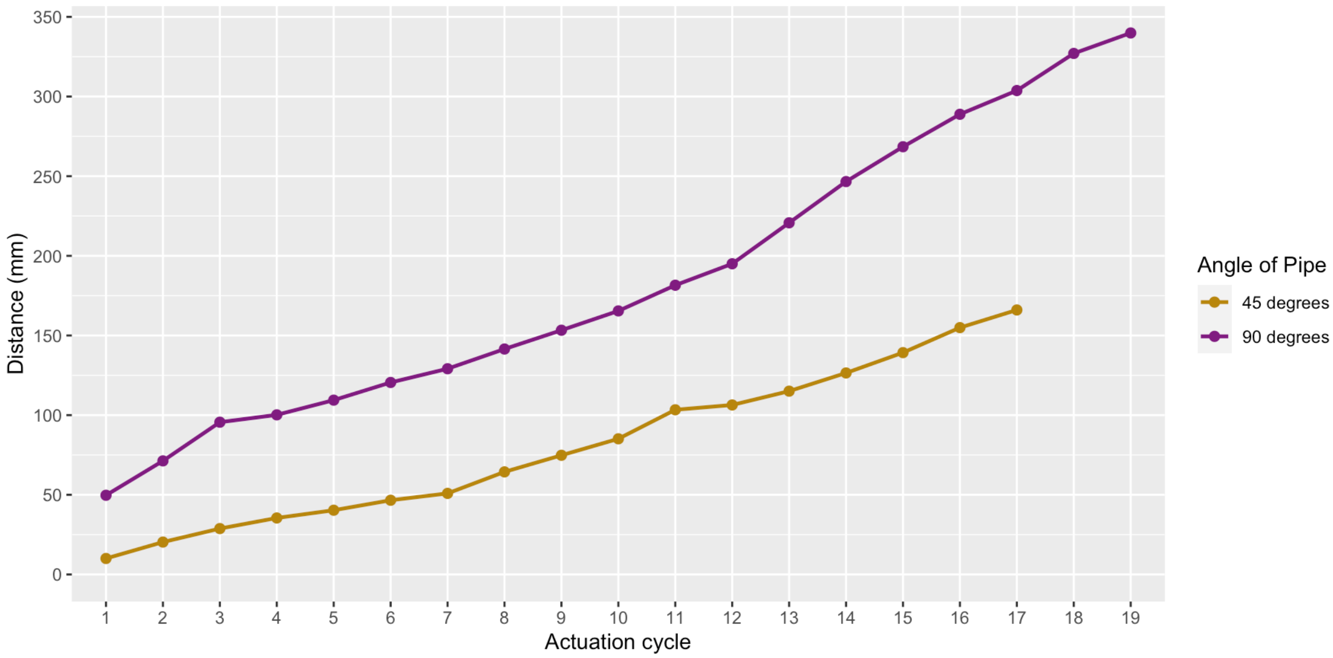

Figure 11: Travel distance by actuation cycle. The interface entered tangential sections of 90 degrees 45 degrees curved cylinders on the 19th and 17th cycles respectively.

hands are busy, the interface crawls down to the lower arm for easier voice input. In this application we modify channels to enfold an accelerometer for detecting the motion of both hands which in turn triggers locomotion. We used an open-soure, miniaturized portable compressor, FlowIO [57], to pressurize the actuators for a wearable context. The FlowIO device is connected directly to the actuators and is programmed to periodically inflate them to a predefined pressure, followed by subsequent exhaustion of the air to produce the desired locomotion. While we demonstrate this in the application of an everyday interaction, we envision it can also be used widely for health and rehabilitation applications. Owing to the channels that can be designed to enfold a wide range of actuators and materials outside what is proposed in this paper, materials such as shape memory alloy (SMA) can be integrated to offer additional functions such as compression. With the freedom in channel design, one can configure lateral channels in addition to the longitudinal ones to enclose SMA along the circumference of arm. The interface would climb up and down the arm to convey compression on varying locations.

6.2 Industrial Applications

The programmability of the *ground layer* and *scales* affords the use of diverse and unconventional materials for knitting. By knitting in a strand of water soluble polyvinyl alcohol (PVA) thread to *ground layer*, we can transform the substrate into an interface that passively reacts to the moisture in the environment. We present an application of a pipe-leakage monitoring and protection sleeve. The interface can travel along the length of a pipe and reach inaccessible regions, and when it gets exposed to water leaks, the PVA thread

Figure 12: KnitSkin, as a wearable interface carrying a microphone, relocates to a suitable location on the arm when answering a phone call.

dissolves and solidifies the entire substrate to stop the leak. By nature of PVA thread, the dissolution induces considerable shrinkage of the substrate, resulting in a tight grip of the interface around the leak location. As the interface dries it remains solid. The resulting interface could serve as a temporary fix for a water leak without requiring external sensing systems (Figure 13).

6.3 Agricultural Applications

We highlight how non-smooth surfaces aid locomotion for KnitSkin. Complying with Filippov *et al.* [20] and the earlier test results from Figure 7, we apply KnitSkin to surfaces with more conspicuous texture. Bark-clad tree branches offer not only an ideal condition for locomotion but also a unique application space. Crawling up vertical trunks and angled branches, KnitSkin can serve as a soft, relocatable tree guard. KnitSkin could offer a simplistic solution

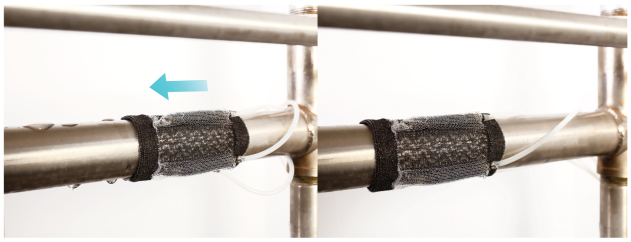

Figure 13: The KnitSkin ground layer can be knitted with a wide range of materials, including water soluble PVA yarn. When KnitSkin travels along a pipe and becomes exposed to water leaks, the PVA yarn dissolves and hardens as the yarn dehydrates. The hardened surface of KnitSkin could form a protective layer on the point of leakage.

Figure 14: By modifying channels into pockets for a portable pesticide dispenser, KnitSkin can further work as an agricultural robot.

to common issues with existing plastic wraps, which leave a nasty abrasion and can result in bark disease due to the excessive moisture captured inside. The porous structure of knits lets air flow freely through the substrate, while maneuvering with least damage to the tree (Figure 14). Alternatively, the *ground layer* could be knitted with insect repellent yarns [4] to protect young trees from insect pests which can be harmful for the tree. If equipped with a portable pesticide spray, KnitSkin could also serve as a minimally intrusive pesticide dispenser that does not spread unneeded chemicals to other trees.

7 DISCUSSION, LIMITATIONS, AND FUTURE WORK

Evaluation. We demonstrated that KnitSkin's effective locomotion strategy was compatible with various terrain characteristics ranging from the surface materials, slope of terrain, and terrain curvature. In extending the evaluation, relations between locomotion performance and other mechanical characteristics of individual actuators and the fabric substrate could further be studied. This could include, expressing travelled distance as a function of normal force of the interface, or characterizing locomotion when actuators undergo different actuation strains. In terms of evaluation, given that it is designed as a single variate study, a multi-variate study could more comprehensively explain the relations among the factors. Finally, in contrast to the current manual approach of logging travel distance, vision-based object recognition through OpenCV could minimize error rate and provide more robust data.

Locomotion on diverse cylindrical surfaces. While KnitSkin operates using inter-facial friction, which is similar to the mechanism proposed by Rafsanjani et al. [52], KnitSkin adds one more crucial determinant for successful locomotion: a moderate amount of normal force via a conformable knit substrate, which is determined by the tightness of the interface. In evaluating performance, our primary focus was to keep the diameter of terrain uniform while having the perimeter circular to keep the two conditions for locomotion—anisotrophic friction and normal force—consistent throughout the traversal. However, as our applications and Supplemental Material suggest, KnitSkin can absorb a moderate degree of irregularities in a terrain. For example, KnitSkin can climb on a cracked surface with rough textures such as tree trunk, as well as moderately tapered terrains such as mannequin arm and human forearm. For future work, further exploration of a helical terrain, or terrains with more exaggerated bumps and depressions could illuminate KnitSkin's broader applicability. To accommodate more challenging terrain geometries, KnitSkin should be designed with a control system that can perceive the terrain ahead and let the interface actively alter its structure. For example, KnitSkin could eventually be equipped with IR sensors to detect a protrusion or depression ahead. A closed-loop system, in which actuators communicate through IMUs to control strain, actuation frequency and exhaust/intake duration could enable locomotion against more challenging terrains. Further, to realize localization of the interface, acoustic beacons or odometry sensors coupled with an external camera could be explored.

Miniaturization and improved portability. For improved portability which is especially important for wearable applications, the compressor should be further miniaturized. With pressure above 30 psi to provide ideal strain, the existing portable compressors such as FlowIO [57] or other miniature air pumps [15] are incapable of providing sufficient pressure, compromising maneuverability. Although KnitSkin still can actuate under a compromised level of pressure, alternative actuators that can generate similar force and strain in comparison to the current pleated actuators should be investigated.

Limitations in current system. KnitSkin is prone to failed performance in certain circumstances. Most importantly, due to the nature of the friction mechanism, KnitSkin is incapable of changing the direction of its motion during operation. It is also possible for the actuation to be disrupted if the surface is characterized with an excessively bumpy texture or sharp protrusions that could potentially catch or puncture the interface. It is also possible that if KnitSkin were to crawl on a surface clad with fibers that are aligned in a specific direction, such as velvet or corduroy, its travel distance may be affected by the direction of the fibers. Also, in circumstances where the normal force of the interfaces changes due to the inconsistency in the terrain diameter, performance is likely to be compromised. In terms of the actuators, the rigidity of the current actuators limits them from bending along the curvature of a terrain could constrain locomotion on terrains with certain angles. Lastly, challenges still remain in implementing KnitSkin on a terrain in which either end is inaccessible. For instance, if KnitSkin interface were to maneuver a tall lamp post, the interface would first have to be cut open and seamed later as it wouldn't be able to slide through the end that is out of reach.

8 CONCLUSION

We presented KnitSkin, a *soft* approach for generating locomotion on cylindrical surfaces. We introduced the fabrication of a knitted scaled skin, which consists of the *ground layer*, the *scales* which contribute to surface friction, and the *channels* for integrating actuators for elongation. We defined the *scales* as the primary contributor to the anisotropic friction of the substrate. We characterized geometric and material parameters of the *scales* for realizing movement. In evaluating locomotion, our experiments revealed the effect of surface materials, the number of actuators, and terrain slope on traveled distance. We also qualitatively inspected locomotion on curved terrains. Drawing insights from the evaluation, we proposed applications across different scales: *wearable*, *industrial*, and *agricultural*. Taking inspiration from nature, KnitSkin exemplifies the versatility of machine knitting in creating a unique bio-inspired substrate that enables underexplored locomotion technologies on cylindrical terrains.

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