

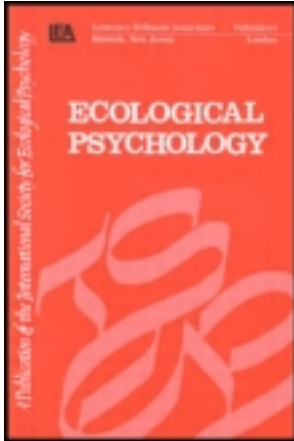
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Bio-Inspired Design of Soft Robotic Assistive Devices: The Interface of Physics, Biology, and Behavior

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Bio-Inspired Design of Soft Robotic Assistive Devices: The Interface of Physics, Biology, and Behavior

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Wearable assistive robotic devices are characterized by an interface, a meeting place of living tissue and mechanical forces, at which potential and kinetic energy are converted to one or the other form. Ecological scientists may make important contributions to the design of device interfaces because of a functional perspective on energy and information exchange. For ecological scientists, (a) behavioral forms are an assembly of whole functional systems from available parts, emerging in energy flows, and (b) nature explores for informationally based adaptive solutions to assemble behavioral forms by generating spontaneous patterns containing fluctuations. We present data from ongoing studies with infants that demonstrate how infants may explore for adaptive kicking solutions. Inspired by the ecological perspective and data from developing humans, ecological scientists may design interfaces to assist individuals with medical conditions that result in physical and/or mental impairment. We present one such device, what is called the “second skin,” to illustrate how a soft, prestressed material, worn on the skin surface, may be used synergistically with synthetic and biological muscles for assisting action. Our work on the second skin, thus far, suggests a set of ecologically inspired principles for design of wearable assistive robotic devices.

Robotic devices are already a major part of the lives of patients with medical conditions that leave them physically and/or mentally impaired. These include (a) robotic orthotic devices (e.g., exoskeletons) used as mobility aids following perinatal brain injury that leads to lifelong disability (e.g., cerebral palsy), accidents resulting in head trauma, or stroke in the aging population (Marchal-Crespo & Reinkensmeyer, 2009); (b) robotic prosthetic devices that replace a damaged or lost limb (Ellenberg, Geyer, & Herr, 2010); and (c) neuroprosthetic systems that serve as an interface between the human nervous system and mechanical replacements for body organs (Konrad & Shanks, 2010). All of these have in common the fundamental requirement of functioning cooperatively with remaining intact body systems.

Engineers are increasingly collaborating with biologists, neuroscientists, biomechanists, and ecological scientists to improve the design of these devices so that, one day, there will be a seamless interface between biological and synthetic systems. A step in that direction has been the use of biologically inspired, or bio-inspired, design principles to advance the science and technology of robotic devices used for assisting mobility and restoring lost nervous system function (Zenios, Makower, & Yock, 2010). The principles guiding these design strategies are not always made explicit but are evident in the kinds of questions that engineers ask their colleagues in biology, neuroscience, and ecological science, such as, “How does a human infant learn to walk?” or “What role do the muscles play in learning to walk?”

WHAT IS BIO-INSPIRED DESIGN?

For centuries, philosophers, natural scientists, tinkerers, and engineers have been intrigued and inspired by life's devices (Vogel, 2003), such as the wing veins and material properties that give insects the ability to outmaneuver predators (Tanaka, Whitney, & Wood, 2011) and the adhesive van der Waals force of bristles that allow the gecko's foot to provide support for gravity-defying acts on sheer vertical surfaces (Autumn, Dittmore, Santos, Spenko, & Cutkosky, 2006). A new era of collaboration between integrative biologists and engineers has resulted in a sharpening of the distinction between bio-mimicry (imitation of nature) and *bio-inspired engineering, the design and fabrication of materials and devices that operate on the same principles as actual organisms without necessarily resembling them* (Flammang & Porter, 2011).

A motivation for this article is to stimulate the interest of ecological scientists in developing wearable robotic devices for assistance and rehabilitation. Ecological scientists may bring three related perspectives to bio-inspired design of wearable robotic devices: (a) a perspective that emphasizes mechanical guidance of exploratory behavior, (b) a functional perspective emphasizing the scaling of muscle activity to the mechanical properties of the surround, and (c) a perspective that treats the development of action systems as the assembly and tuning of high-degree-of-freedom systems into lower dimensional task-specific devices. The purpose of this article is to introduce a new, wearable, robotic device to assist mobility of infants and young children, being developed in our laboratories, as an illustration of how these three ecological perspectives may guide design.

INTERFACES

Understanding the intersection between biology and mechanical forces requires a framework that incorporates both. Here, we propose an ecologically inspired concept, an *interface*, the meeting place of living tissue and mechanical forces at which potential and kinetic energy are converted to one or the other form. Interfaces are at the heart of a number of disciplines that integrate the physical and biological worlds. Ecological scientists, as part of the integrative biology community, have been intrigued by the fundamental *behavior* patterns revealed at the *interface* between biological forms and the physical world (Gibson, 1966; E. C. Goldfield, 1995; Warren, 2006). The insights and empirical findings of ecological scientists may have a great impact on design of human-robot interfaces to assist and restore lost function.

In developmental biology (Mahadevan, 2008; Mammoto & Ingber, 2010), physics and biology meet at the interface between the extracellular matrix and a solid or liquid substrate. Problems of interest that may be studied at such interfaces include motility mechanisms that adapt to surface properties and the transmission of mechanical forces via cytoskeletal structures (a process called mechano-transduction). In the field of comparative biomechanics (Thompson, 1942; Vogel, 1988, 2003), the perspective is that living systems are bathed in force fields, including gravity, fluid vortices, and the wind; they make contact with solid objects and interact with other living creatures. Scientists in this field aim to understand how plants and animals harness physical law to do work, as when fish exploit vortices that arise from fluid flow around stationary objects or movements of other animals (Lauder, Anderson, Tangorra, & Madden, 2007; Liao, Beal, Lauder, & Triantafyllou, 2003) or when the beetle *Potamodytes tuberosus* maintains an oxygen-extracting bubble in a shallow, torrential stream (Vogel, 1994). Finally, biomechanics and dynamical systems meet neuroscience in the field of neuromechanics (Holmes, Full, Koditschek, & Guckenheimer, 2006; Nishikawa et al., 2007), which emphasizes the way that the nervous systems harnesses the body's multifunctional elastic resources (muscle, elastic tissue properties) to minimize energy expenditure during locomotion. All of these subdisciplines involve energy exchange at the interface of mechanical forces and force-transducing tissue. The same process by which material is sculpted by fields of forces at cell and tissue scale may also hold for more macroscopic forms, including body shape changes during locomotion.

A challenge in the design of interfaces between humans and wearable robots is how to provide information for assistive control that allows the robot to respond at timescales commensurate with the timing of biological control. Biological control of action involves muscle activation influences occurring in parallel with different amounts of delay, including threshold-based feedforward (Pilon & Feldman, 2006); preflexive (zero-delay) control based upon the mechanical properties of muscle, fascia, and other body tissue (Turvey, 2007); control based upon the interneuronal circuitry of the spinal cord (Tsianos, Raphael, & Loeb, 2011); and control modulated by the various time delays related to the flow of energy through brain networks with changing patterns of synchronization (Deco, Jirsa, & McIntosh, 2011). These timing characteristics of sensorimotor control motivate an interface design for wearable robots in which (a) the substrate architecture is patterned with passive and active elastic materials, so that force production is contributed by both elements with zero time delay, and by longer delay sensor-modulated muscular resources; (b) different types of sensors (e.g., strain, inertial) provide information that both preattunes the substrate and provides feedback for muscular activation; and (c) there is distributed control based upon self-assembling modules that are rapidly recruited for collective actuation. What might be a bio-inspired basis for the design of

an architecture capable of embodying delays in energy flow as the basis for sensorimotor control in biological systems?

PRESTRESSED TENSEGRITY STRUCTURES, MECHANICAL BIOLOGY, AND TENSEGRITY ROBOTS

Nature has incorporated physical law into the architecture of the internal structure of individual cells and into the body plans of multicellular collectives (i.e., animals and their body organs; Thompson, 1942; Vogel, 1988, 2003). One model of the embodiment of physical law in biological systems is the prestressed tensegrity structure (Ingber, 2003a, 2003b, 2010; Wang, Tytell, & Ingber, 2009). Prestress is defined as preexisting tensile stress, or isometric tension, within a structure; a prestressed architecture able to stabilize its shape by continuous tension, or tensional integrity (rather than compression), is called a tensegrity structure (Ingber, 2003a). At the cellular level, there is evidence that the entire cell may be a prestressed tensegrity structure (Mammoto & Ingber, 2010). The tensional integrity is provided by a cytoskeletal lattice consisting of interconnecting microfilaments, microtubules, and intermediate filaments. The microfilaments, a network of contractile filaments throughout the cell, are a cellular skeleton, or cytoskeleton, exerting tension by pulling the cell membrane toward the nucleus. Opposing this inward pull are both the internal microtubules and the extracellular matrix. The intermediate filaments act as stiffening elements, connecting microtubules and contractile microfilaments to each other and to the surface membrane and cell nucleus (Huang & Ingber, 1999).

The insight that cell architecture may be based upon a structure of prestressed interconnected elements has promoted numerous experiments that examine the role of mechanical influences in the development of complex morphologies, such as organ systems (Ingber, 2010). The material properties of embryonic organ systems, including the heart, lungs, and musculoskeletal system, appear to adapt to changes in the physical demands on their function that occur at particular developmental stages (Mammoto & Ingber, 2010). For example, in zebra fish embryos, waves of contraction and elastic deformation of the heart chamber travel forward and reflect back to generate suction forces that drive blood flow even before valves form (Forouhar et al., 2006; Rieffel, Valero-Cuevas, & Lipson, 2010).

There are at least two implications of the tensegrity model for the design of interfaces for robotic assistive devices worn on the body. First, an assistive device with a prestressed mechanical structure may provide the basis for a zero-delay information transmission and control system, what Rieffel et al. (2010) call “morphological communication.” Second, an interface capable of actively changing the balance of forces acting on the entire body (e.g., by detecting

changes in the body center of mass), rather than adding force or torque to assist a particular muscle (as is common in current exoskeletons), may reduce the burden of control of a high-dimensional degree-of-freedom system. One example of an attempt to incorporate tensegrity into the design of a locomoting robot is the “tensegrity robot” (Paul, Valero-Cuevas, & Lipson, 2006), a three-strut, nine-cable triangular tensegrity prism. By varying the equilibrium length of the cables, different aspect ratios between the width and length of the structure were achieved (Paul et al., 2006). Moreover, application of a force on one part of the structure causes a global deformation of the structure so that a small number of actuators may cause a global movement pattern. Finally, multiple subsets of actuators may be used to produce the same behavior.

SOFT ANIMALS, HYDROSTATIC ORGANS, AND SOFT ROBOTS

Extant assistive wearable robots, often called “exoskeletons” (Ferris, 2009), are distinguished by a rigid structure that makes them heavy, inflexible, and uncomfortable to wear. As their name implies, exoskeletons externalize the internal skeletal support structure of vertebrates, including joints and tendonlike elements. Even current tensegrity robots use rigid elements as struts. However, from the standpoint of bio-inspired design, there may be other sources of structural support that may be used in place of rigid elements. For example, in animals such as worms, in octopus limbs, and in internal organs that include the human tongue (Smith & Kier, 1989), nature has discovered another solution: soft architectures. Unlike rigid structures, soft architectures are able to assume the shape of the substrates with which they come in contact, giving them remarkable flexibility and versatility.

An example of a soft-bodied animal is the larval stage of *Lepidoptera*, the caterpillar. Caterpillars have a wormlike body plan consisting of a cylindrical segmented body wall, within which are viscera and internal organs. A caterpillar body has bilateral pairs of nonarticulated stubby “prolegs” attached to each body wall segment. New imaging techniques have revealed that caterpillars use the muscles of the digestive viscera as well as the prolegs for hydrostatic locomotion (Simon et al., 2010). With each step, the viscera slide to and fro, like a piston within the body wall, so that the mechanical properties of the contained organs are exploited for locomotion. Caterpillars are particularly intriguing because of the way they locomote while hanging upside down. H. Lin & Trimmer (2010) have shown that caterpillars use not only hydrostatic pressure to control sag of their body against gravity but also their prolegs as anchors to lock sections of the abdomen to a substrate as a means of support, a kind of “environmental skeleton.” Thus, the substrate becomes a part of the animal’s functional activities,

relaxing any requirement for a rigid internal skeleton. For a soft-bodied device worn on human limbs, it may similarly be possible to attach the elastomeric material to lines of force along the body surface that are inextensible as a means of support. We return to this point later.

The human tongue anatomy is characterized by an interwoven network of skeletal muscle fibers and fiber bundles, involving both intrinsic fibers, those with no connection to bony surfaces, and extrinsic fibers, those possessing connections to bony surfaces (Gilbert & Napadow, 2005). Recent diffusion tensor MRI studies have found that the tongue is best considered a continuum of heterogeneously oriented muscular elements rather than a set of distinct muscles (Gilbert, Napadow, Gaige, & Wedeen, 2007). This intricate array of fibers, aligned at various angles orthogonal to the direction of deformation, may be the structural basis for what is called hydrostatic deformation. For example, during human swallowing, a series of deformations results in the transport of ingested food from the mouth to the esophagus (Goldfield et al., 2010; Miller, 1993). How do large numbers of fibers of varying alignments achieve the mechanical functions of swallowing, such as containing the bolus in a grooved depression in the middle portion of the tongue's dorsal surface, transferring the bolus to the posterior oral cavity, and propelling the bolus to the pharynx? The answer is apparent through the use of MRI-based strain maps that illustrate the synergic action of fibers with particular orientations (Gilbert et al., 2007): each of these swallowing functions is achieved by collective changes in strain, indicating synergic action of fibers within regions of the tongue anatomy. Developmental studies have found videofluoroscopic evidence of synergic tongue actions and changes in the phasing of these synergies with introduction of fluids that vary in viscosity as soon as newborn infants begin to swallow (E. C. Goldfield, 2007). Thus, information provided by deformation within materials may be critical for guiding the assembly and dissolution of synergic actions, as we demonstrate for wearable robots.

An approach to design and fabrication of robots that is inspired by soft animals and hydrostatic organs is called soft robotics (H.-T. Lin, Leisk, & Trimmer, 2011; Shepherd et al., 2011). Soft robots are composed exclusively of soft materials (elastomers, polymers) that offer the possibility of simplifying the more complex mechanical structures used in hard robots. For example, a bendable structure of a soft robot may act as a hinge joint without the complexity of a multicomponent mechanical structure. Soft materials are also amenable to fabrication techniques, such as soft lithography and origami (Martinez, Fish, Chen, & Whitesides, 2012), which greatly simplify and accelerate the design and fabrication process. One example of an innovative architecture for actuation of soft robots is the pneu-net, a series of chambers embedded in a layer of extensible elastomer and bonded to an inextensible layer (Ilievski, Mazzeo, Shepherd, Chen, & Whitesides, 2011). The design and fabrication of second

skin synthetic muscles embedded within a soft, elastomeric material, described later, adopts a similar approach but has not yet fully achieved the functionality of muscular hydrostats.

MECHANICAL GUIDANCE OF EXPLORATORY BEHAVIOR

Spontaneous exploratory behavior at all organizational levels is guided by mechanical information. For example, human neocortical networks form during ontogeny as a consequence of interactions between migrating neurons, or neuron processes, with transient cells that are present at particular gestational stages (Rakic, 2009). Human cortical neurons are generated in a region called the ventricular zone. Specialized glial cells provide migratory radial and tangential pathways along which successive generations of cortical neurons are guided (Rakic, 2009). Physical traction forces that are exerted during brain development influence the thickness of the human cerebral cortex gyri and sulci as well as the shapes of the neurons themselves: neurons located in deep layers of gyri are squeezed from the sides and appear elongated, whereas those that reside in the deep layers of the sulci are stretched and flattened (Hilgetag & Barbas, 2006; van Essen, 1997). The guidance of exploratory behavior is highlighted by the finding that misplaced neurons may be involved in a variety of idiopathic neurological disorders, including childhood epilepsy, mental retardation, autism, and developmental dyslexia (Metin, Vallee, Rakic, & Bhide, 2008).

Mechanical information also guides exploratory locomotor activity. For example, Mahadevan (Korta, Clark, Gabel, Mahadevan, & Samuel, 2007; Mahadevan, Daniel, & Chaudhury, 2004) and others (Sauvage, Argentina, Drappier, Simeon, & DiMeglio, 2011) have studied the emergence of locomotor patterns in the contact mechanics at the interface with a substrate, both in wormlike motions of slender, inanimate hydrogel rods and in animals such as the nematode *Caenorhabditis elegans*. In one experiment with inanimate objects, a soft, slender, cylindrical form (a hydrogel rod) was placed on a soft substrate, a thin film of rubber with straight incisions. The high water content of the rod allowed it to alternately slip and stick, moving through creeping, crawling, inching, and slithering locomotor modes as the substrate was mechanically vibrated. In *C. elegans* studies, different gaits emerge as a response of haptically guided locomotory circuits to changing mechanical load, for example, when increasing the viscosity of the substrate (Sauvage et al., 2011). By changing gait in media whose viscosity is experimentally manipulated, *C. elegans* is able to maintain the “angle of attack” of its undulation with limited muscle power expenditure (Sauvage et al., 2011). In simulations of lamprey swimming, identical muscle activation patterns can produce different kinematics, depending upon body stiffness, indicating that body motions emerge as a balance between

fluid forces and internal muscle and spring forces (Tytell, Hsu, Williams, Cohen, & Fauci, 2010). Other studies of the interactions between neural control, body properties, and hydrodynamics indicate that fish control fin curvature to create vortices that enhance the thrust produced by the tail (Fish & Lauder, 2006; Lauder et al., 2007; Tytell et al., 2010).

NATURE EXPLORES FOR ADAPTIVE SOLUTIONS BY GENERATING SPONTANEOUS PATTERNS CONTAINING FLUCTUATIONS

Spontaneous exploratory activity is ubiquitous at all levels in the organization of living creatures. For example, spontaneous exploration is evident in the behavior of cytoskeletal microfilaments maintaining a balance of forces within the cell (Kirschner & Gerhart, 2005; Wang et al., 2009), in the motility of cortical neurons (Rakic, 2009), in brain (Deco et al., 2011), and spinal (Waldenstrom, Christensson, & Schouenborg, 2009) networks, in a foraging swarm of ants (Holldobler & Wilson, 2009), and in general movements by human fetuses and newborns (Einspieler & Prechtl, 2005; Hadders-Algra, 2002). All of these examples illustrate spontaneous activity that operates at the edge of instability but enters into regular stable regimes (Rabinovich, Varona, Selverston, & Abarbanel, 2006). The transition between stable states is made possible by elements that are chaotic, that is, deterministic but with rich fluctuations that may exhibit what dynamicists call “intermittency,” the tendency for the fluctuations to vary in size and to do so in a deterministically chaotic way (Ihlen & Vereijken, 2010; Peitgen, Jurgens, & Saupe, 1992). Consider, for example, the marine mollusk *Clione limacine*, a highly buoyant planktonic animal that must produce continuous motion in order to maintain its preferred heads-up orientation. Orientation information is provided by an elegant gravity-sensing organ called the statocyst. It has been modeled as a six-receptor neural network ring surrounding a freely floating stonelike structure, called a statolith, whose motion is influenced by the gravitational field (Levi, Varona, Arshavsky, Rabinovich, & Selverston, 2004). Two different stable regimes of *Clione* networks, corresponding to two distinct modes of hunting-swimming behavior, emerge when a network that includes chaotic oscillators synchronizes its activity in a particular way. Thus, in *Clione*, nature uses chaos for the organization of functionally specific adaptive behavior.

In animals with a long period of ontogeny, including humans, a rich substrate of chaotic processes may be the basis for exploring the functional properties of the body (E. C. Goldfield, 1995; Thelen & Smith, 1994). From the newborn period onward, the temporal distribution of clusters of spontaneous behaviors fluctuates dramatically. Intermittency in human infant behavior may be an in-

dication of the continuous nonlinear (i.e., multiplicative) interplay of stochastic and deterministic components across very many scales in the information flow between body and brain. Probing intermittency in a spontaneous behavior, such as kicking, could provide a window on the process by which nature uses brain networks, such as resting state networks (Zhang & Raichle, 2010) to explore body mechanics.

What properties of the legs might be a basis for information exchange between body systems and brain networks? The body consists of multifunctional mechanical components—bones, muscles, tendons, and other nonmuscular tissue with elastic properties. These components may be used in different ways to perform many kinds of work: each leg may become a rigid strut for postural support or a spring system for gait. The multifunctional leg has been modeled in many different animals as a mass-spring system (Holmes et al., 2006; Holt, Saltzman, Ho, Kubo, & Ulrich, 2006; Nishikawa et al., 2007). Active kicking may reflect a nonlinear coupling of brain network oscillations—themselves exhibiting intermittent chaotic dynamics—to an excitable mechanical system, with the muscles re-exciting the intrinsic oscillations of the leg's pendular dynamics as energy is lost. If infant kicking exhibits intermittency due to nonlinear interactions, this may begin to clarify the nature of the process by which flexibly assembled couplings of mechanical components enact network functional connectivity.

A recent study in our laboratory of exploratory supine kicking by typically developing prewalking infants (Stephen et al., 2012) examined whether the mechanical properties of the legs may induce “upstream effects” in which energy fluctuations in the motor periphery (measured at the hip, knee, and ankle joints) influence the developing nervous system. We were interested in determining whether, during spontaneous (exploratory) supine kicking of these young infants, there was already evidence of differentiated mutual influences of the hip, knee, and ankle on each other's joint rotations related to their later functions in walking. For example, the role of the hip is related to initiation of transitions between stance and swing phases of alternating stepping (Thelen & Ulrich, 1991), and so dominance of the hip's contribution to spontaneous supine kicking may be an indication that the hip's functional role for gait is already being established much earlier in development. At the same time, the role of the foot as the physical contact interface between infant and support surface in stepping invites the hypothesis of measurable effects of the more distal parts of the leg on the hip.

Exploratory movements serve to register the surrounding bath of force fields and so to engender a flow of information from the environment to the more central structures regulating organism behavior (Figure 1). The exploratory coupling between organism and environment must occasion just such a distal-to-proximal flow where changes at the motor periphery stimulate later changes in the central regulatory structures of the motor system. We sought to probe the dynamics

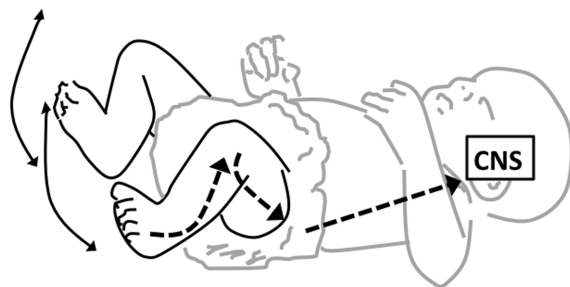


FIGURE 1 Schematic of the proposed flow of information during supine infant kicking. Solid curved arrows on the left signify kicking movements of the feet. Dashed arrows signify the proposed chain of distal-to-proximal interactions through which fluctuations from kicking within surrounding force fields propagate from the motor periphery toward the central nervous system (CNS).

of infant spontaneous kicking for evidence of this distal-to-proximal flow of information.

Documenting the flow of information requires identifying empirical markers of how well organisms detect information. Recent work has suggested that the detection of information for perception–action may be indexed by multifractal fluctuations in exploratory movements (Dixon, Holden, Mirman, & Stephen, 2012). That is, fluctuations composing exploratory movements exhibit a variety of fractal scaling exponents, and this rich variety of fractal scaling exponents predict the changes in the use of contextual energy distributions for perceptual judgments, both across time and across participant (Stephen & Anastas, 2011; Stephen, Arzamarski, & Michaels, 2010; Stephen & Hajnal, 2011). Multifractal fluctuations during exploration of the task environment appear to mirror multifractal fluctuations available in the task environment. Furthermore, this mirroring is not simply of the environmental fluctuations “on average,” that is, the additive structure (i.e., mean, variance, and autocorrelation; Theiler, Linsay, & Rubin, 1994) but it rather reflects sensitivity to the multifractality attributable to multiplicativity in the fluctuations, above and beyond the aggregate, additive structure (Stephen & Dixon, 2011). That is to say, it may be possible to identify flows of information by examining flows of multiplicative multifractal fluctuations and thus to bring new rigor to tests of the exploratory aspect of spontaneous movements.

We sought to bring these notions to bear on infant spontaneous kicking (Stephen et al., 2011). That is, if exploration at the scale of the organism–environment relationship could be considered the propagation of multiplicative multifractal fluctuations, it is possible that spontaneous kicking might exhibit similar propagation of multiplicative multifractal fluctuations. Whereas previous

work had only considered the flow of information between organism and task environment, we were curious whether similar statistical relationships might be found among components of the motor system, that is, between ankle and knee, between knee and hip. Perhaps the activity of different joints along the leg might show a similar pattern of multifractal fluctuations spreading from one to the other. If the pattern of multifractal fluctuations reveals effects of multiplicativity from more distal joints (e.g., ankle) to more proximal joints (e.g., hip), this evidence would confirm the exploratory aspect of spontaneous kicking in human infants. In other words, if relatively proximal joints absorb the multiplicative fluctuations of relatively distal joints, then we begin to see specific evidence of spontaneous kicking movements ferrying information about the surrounding force field bath toward the central nervous system.

We tested these ideas in a preliminary study with four infants (Stephen et al., 2011). We used motion capture to generate joint-angle time series for the ankle, the hip, and the knee for several consecutive 30-s intervals. We computed the multifractality for each original time series as well as for 50 surrogate time series each mimicking the aggregate, additive structure. We scaled the original series' multifractality by the average multifractality of the surrogates to derive a ratio expressing the degree of multiplicativity. We modeled how this multiplicativity ratio changed across the three joints for each leg using vector autoregression (VAR), a modeling strategy used to assess mutual effects among interacting, bidirectionally coupled variables (Lutkepohl, 2005). VAR modeling controls for the autoregressive behavior of each individual variable while shedding light on the unique effects of each variable's current behavior on each other variable's later behavior. VAR modeling showed that there were distal-to-proximal flows of multiplicative multifractal fluctuations on both legs, as evidenced by positive impulse responses in multiplicativity ratios from ankle to knee, from ankle to hip, and from knee to hip (Figure 2). Thus, we found evidence that multiplicative multifractal fluctuations at the relatively distal joints engender multiplicative multifractal fluctuations at relatively proximal joints. The similarity of this result to previous work (Stephen & Dixon, 2011) examining the relationship of exploratory movements to task environment leads us to interpret these distal-to-proximal relationships as evidence of the exploratory benefit of spontaneous kicking.

THE SECOND SKIN: A SOFT ROBOTIC ASSISTIVE DEVICE FOR MECHANICAL GUIDANCE OF EXPLORATORY ACTIVITY

The second skin is a wearable, assistive robot whose form and function reflect one attempt to incorporate the perspective of ecological science into bio-inspired

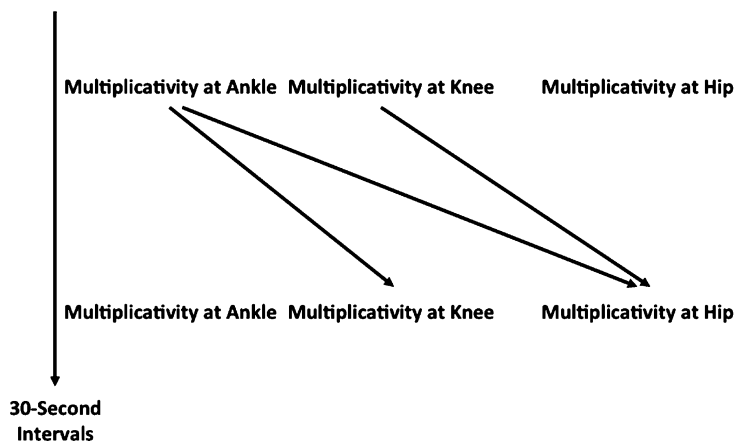


FIGURE 2 Schematic of distal-to-proximal effects among leg joints across subsequent 30-s intervals, with time progressing downward along the vertical axis. Arrows relating multiplicative fluctuations at each joint indicate the distal-to-proximal effects of multiplicative fluctuations at one joint or another. Multiplicativity at the ankle promotes multiplicative fluctuations at the knee and at the hip. Multiplicativity at the knee also promotes multiplicative fluctuations at the hip.

device design (see Figure 3). The second skin is a type of soft robot (Shepherd et al., 2011) worn over the skin surface as an assistive device for individuals with limited mobility across the life span. In its passive mode, these soft, active materials detect motion without interfering with the natural host mechanics. When

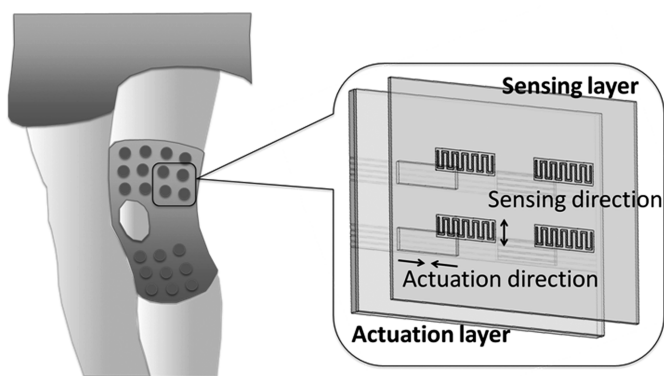


FIGURE 3 A conceptual rendering of the second skin device. Note the layered architecture in which sensors and synthetic muscles are functionally integrated, like Golgi tendon organs and biological muscles.

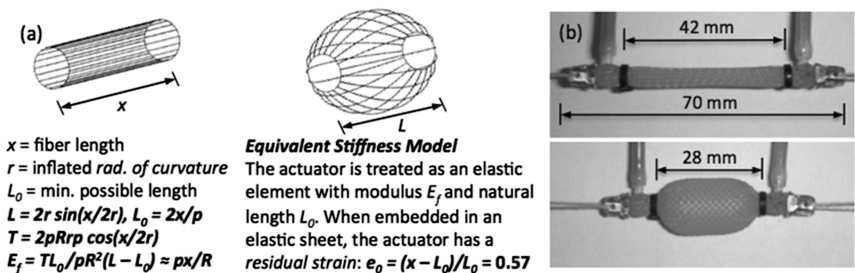


FIGURE 4 Miniaturized pneumatic actuator, a synthetic muscle. (a) Analytical models with different fiber configurations. (b) Actual prototype showing contraction with compressed air.

active, though, the materials are capable of exerting assistive forces (torques) through dramatic, but reversible, changes in shape and elastic rigidity. The second skin spans multiple joints to assist in maintaining postural orientation, gait, reaching and grasping, manipulation, gestural communication, and other skills. In its current stage of prototyping, the second skin adopts a modular architecture based on an elastomer-sealed network of conductive liquid sensors and pneumatically driven miniature actuators (synthetic muscles). Electronics, communications, and pneumatic control are all accomplished on board with miniaturized boards, stretchable electronics and sensors, and spatially distributed microvalves and pneumatic actuators.

The overall structure of the second skin is a layered, conformable material with embedded soft pneumatic synthetic muscles and strain sensors. Each synthetic muscle, a miniature pneumatic actuator, is composed of inextensible thread wrapped around a rubber cylinder. Each pneumatic muscle (see Figure 4) is equipped with a hyperelastic strain sensor (see Figure 5) that detects the shape change of a synthetic muscle contraction. Four muscle cells with strain sensors

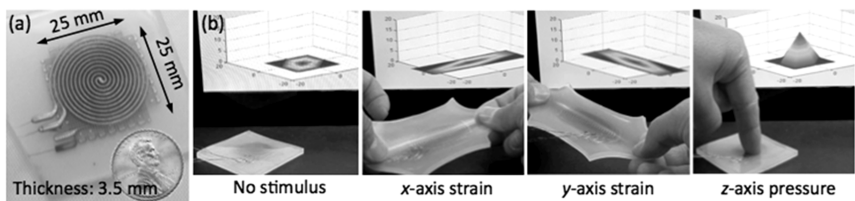


FIGURE 5 Hyperelastic strain sensor, a synthetic Golgi tendon organ. (a) Actual prototype. (b) Multimodal sensing capability.

are controlled by one microcontroller as a modular unit. A network of programmable embedded controllers, connected logically and spatially, controls the modular units. Multiple synthetic muscles are actuated (contracted) collectively as a group in order to generate a collective displacement.

IMPLICATIONS OF ABUNDANT ELEMENTAL VARIABLES FOR ASSISTED EXPLORATORY BEHAVIOR: RELATION BETWEEN PARTS AND THE WHOLE

The abundance of muscles and joints of the human body provides a rich set of possibilities for motor equivalence, performing the same action in different ways, for example, through covariation of joint rotations (Latash, Krishnamoorthy, Scholz, & Zatsiorsky, 2005; Turvey, 2007). We can see this abundance, for example, in the foot trajectory of a 3-month-old infant kicking vigorously in our motion capture laboratory while lying supine (see Figure 6). However, despite an abundance of foot trajectories, at this age there is little flexibility in the activation of muscles for limb flexion and extension: muscles are coac-

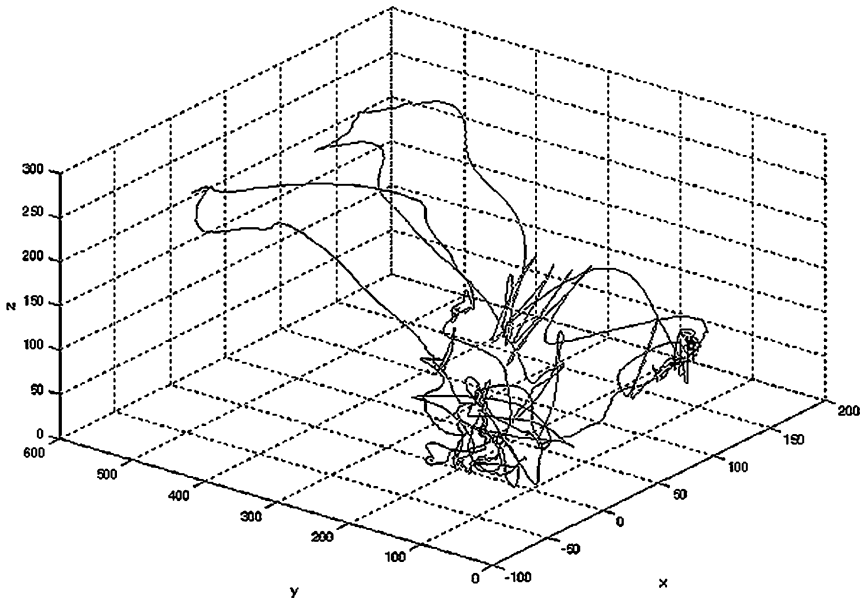


FIGURE 6 Foot end point trajectories of multiple kicks of each leg by a young infant lying supine.

tivated with each joint rotation so that infants are not using the muscles in a way that takes advantage of the effects of gravity on the leg (see Thelen, 1985).

When typically developing toddlers take their first steps at around age one, the activation of particular muscle combinations during particular phases of the gait cycle is identifiable but still quite variable (C.-L. Chang, Kubo, Buzzi, & Ulrich, 2006; Dominici et al., 2011). With weeks of walking experience, muscle activations remain variable, but there is a dramatic stabilization of end point (foot placement) variables (Dominici et al., 2011). These findings suggest that during the developmental period between 3 and 12 months, well before they actually take their first steps, young children may discover through exploratory behavior the relation between the parts (e.g., joint rotations) and the functional whole (e.g., leg length). If this hypothesis is correct, it implies that one way to assist brain-injured children is to use a robotic device (such as the second skin) to *provide young children with an abundant set of part-whole body relationships, which they may not be able to generate on their own*. By providing appropriate postural supports, the second skin may be used to systematically provide abundant information for exploratory learning. This strategy may be generalized during other periods of the life span, for example, for adult wounded warriors and aging adults who have suffered a stroke.

As an initial test of the hypothesis that typically developing infants are exploring part-whole body relationships, we recently examined spontaneous kicking by a group of healthy 4- to 6-month-old infants. Our expectation was that the variability of rotations at each joint, over multiple kicks, would be high, but at the same time, a measure of leg length, the hip to ankle distance, would remain relatively invariant. The hypothesis was confirmed: joint rotations at the hip and knee were highly variable over repeated kicks (but hip-ankle distance showed little variability). We were not simply measuring the maximum length of the leg during extension. When we measured the actual leg lengths and the hip-knee distance during kicking, they were significantly different, $p < .05$. This finding is consistent with research on cat locomotion and adult hopping (Auyang, Yen, & Chang, 2009; Y.-H. Chang, Auyang, Scholz, & Nichols, 2009), which demonstrate that the leg is controlled as a low-dimensional “device,” a telescoping spring system or shock absorber. Further analysis of the infant data using the uncontrolled manifold method (Latash et al., 2005; Scholz & Schoner, 1999) may reveal more detail about the nature of the information being explored.

Clearly, the relation between joint rotations and whole-limb behavior is not the only information about part-whole relationships available to young children as they learn to walk. Other relationships include variables that stabilize mediolateral oscillation while relaxing anterior displacement (Kubo & Ulrich, 2006) and phasing of escapement pulses on the right and left sides of the body in order

to sustain the gait cycle (Holt et al., 2006), all potential questions of interest for ecological scientists designing assistive devices.

Our preliminary findings with infants have helped guide the design of a bio-inspired robotic control system in which groups of synthetic muscles (parts) are rapidly recruited to flexibly change the length and shape of a soft cylinder (a telescoping whole). We fabricated functional units consisting of a miniaturized pneumatic actuator and hyperelastic strain sensor in successive layers. Filling each actuator with compressed air resulted in a length change that constituted a feedback loop for detecting synthetic muscle contraction. The system software architecture is divided into two main layers: System Services Layer (SSL) and Application Layer (AL; see Figure 7). The former implements fundamental components that manage local resources and provide primitives to support algorithms at the AL. The SSL implements a clock-driven scheduler, handles intermodule communication with neighboring modules, accesses strain sensor readings, and sets actuation parameters. The AL specifies the application goal using the services provided by the SSL. The clock-driven scheduling provides predictable execution of specific tasks at individual modular units, allowing simplification of control on timing of sensing, processing, and actuation tasks.

The basis for a second skin capable of forming assistive synthetic muscle synergies was demonstrated by fabricating a soft, flexible, hollow elastomeric cylinder with 16 integrated muscle-sensor units (Figure 8). This was used to conduct experiments that demonstrated collective actuation for contraction and bending. The figure illustrates how contraction by particular combinations of muscles results in cylinder shape changes.

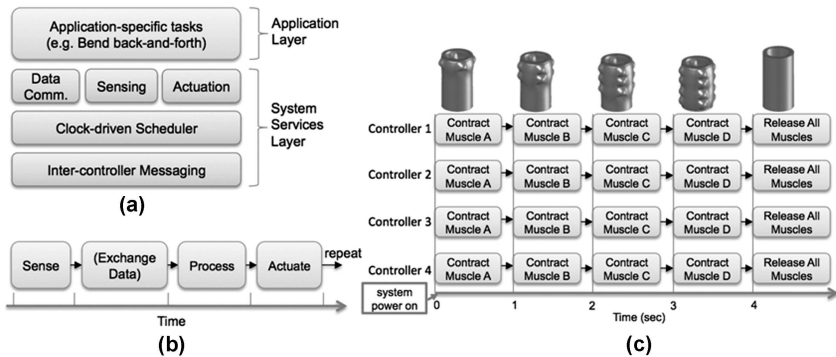


FIGURE 7 (a) Second skin software architecture. (b) Controller program schedule. (c) Example program of sequential contraction of synthetic muscles working cooperatively.

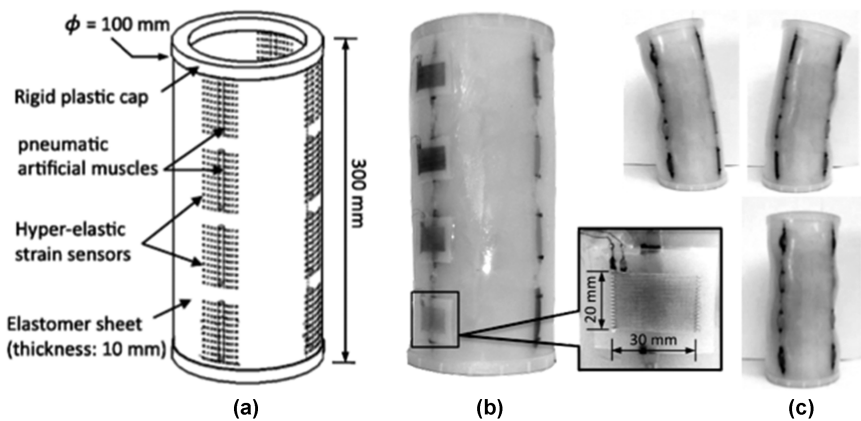


FIGURE 8 A modular architecture for the second skin design, with 16 sensor-actuator integrated units in a cylindrical form. (a) Prototype design. (b) Actual prototype with a sensor-actuator unit magnified. (c) Examples of contraction and bending shape changes of the cylinder.

SCALING SECOND SKIN MATERIALS AND SYNTHETIC MUSCLES TO THE MECHANICAL PROPERTIES OF THE BODY AND THE SURROUND

To create a garmentlike second skin that is comfortable, supportive, and allows a full range of motion, the second skin architecture is based upon the behavior of the body's soft tissue envelope during limb flexion–extension. Figure 9 illustrates

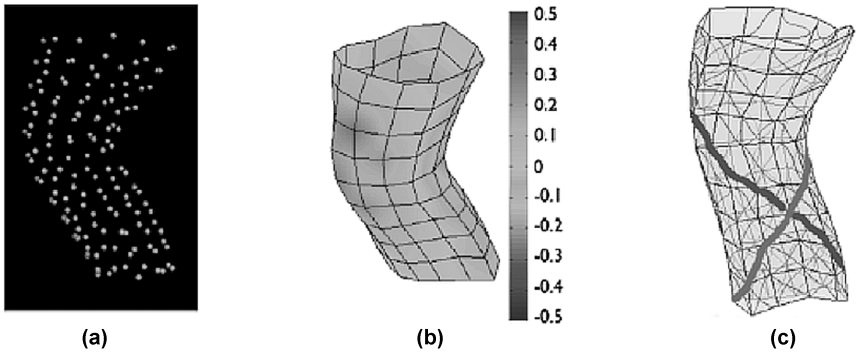


FIGURE 9 A patterning of strain fields across the skin surface using (a) motion capture data. The analysis generates (b) longitudinal strain data and (c) lines of nonextension.

one design approach we are using to optimize the placement of rigid longitudinal elements attached to another set of rigid elements encircling the waist. The approach is based on the early work of Iberall (1964) on development of space suit designs and more recent work on an astronaut “bio-suit” (Newman, Bethke, & Carr, 2004). These “lines of nonextension” are a bit like internal “suspenders” that counteract the torques generated by the contraction of the longitudinally arrayed synthetic muscles without potentially uncomfortable compressions of the skin. The illustration in Figure 9 is based upon information from an eight-camera VICON motion capture system that tracked 144 reflective markers on the leg at the knee (leftmost panel) during flexion-extension. Marker position changes were used to calculate second-order Lagrangian strains over the entire motion. Then 3-D projections, rotations, and eigenvector analysis of individual strains gave longitudinal, shear, and principal strains for the marker positions (central panel). Finally, the principal strains were used to mathematically determine the angles of lines of nonextension, projected onto the leg and connected as continuous lines. The rightmost panel presents the results of an algorithm that plotted minimum strain lines in diagonals across the back of the knee. We extend this methodology to a more complete synthetic soft tissue patterning.

With a soft prestressed material as a design foundation for a tuned garment, what are the requirements for assistive actuation by synthetic muscles? Commercially available pneumatic (McKibben-type) actuators are typically large and contain rigid components not compatible with a soft, tuned material worn on the skin surface. For a prototype garment, we used the miniature pneumatic actuator design described earlier, as part of an embedded architecture of synthetic muscles arranged along the longitudinal axis of the leg, within a soft (not yet prestressed) material. We have also developed a portable, low-profile, lightweight gas storage and distribution system to power the synthetic muscles. As compressed gas is valved into a synthetic muscle, the tubing expands, pressing against the sheathing, causing the fiber angle to change and shortening the device. The amount of shortening can be prescribed by choosing the appropriate initial free length of the device.

After characterizing the actuator power output and the capacity of the portable gas supply system, we conducted studies to determine the requirements for powering synthetic muscles to assist the biomechanical characteristics of an engineered model ankle scaled to the size, form, and weight of a 50th percentile 4-year-old child. Our goal was to produce assistive actuation for active plantarflexion and dorsiflexion with force, power, and range equivalent to values derived from child gait; produce active inversion and eversion; and avoid restricting natural movement in other (passive) degrees of freedom. The anthropometric data was derived from the 2005 Centers for Disease Control Anthropometry Study (McDowell, Fryar, Hirsch, & Ogden, 2005) and published research reports (e.g., Hallemans, DeClercq, Otten, & Aerts, 2005).

We present an example of assisted actuation of our engineered foot-ankle model using 120 mm long actuators that, together, provide 30° ankle rotation (Wehner et al., 2012). Each actuator provided 100 N, generating a moment of 4 Nm. We determined that the system required 19.95 Nm, so we used six actuators for slightly more assistive power than was needed. The engineered foot-ankle model consisted of an aluminum inner structure terminating at the ball of the foot and surrounded by a humanlike silicone form, providing a rigid inner structure from the heel to the ball of the foot, which had one passive degree of freedom. Dorsiflexion actuators were attached to Kevlar line acting as tendon analogs and routed through short Teflon tubes attached in locations similar to human tendon sheathing. A spread-harness configuration at the muscle origin points near the knee was used to distribute forces, minimizing local contact pressure. Finally, the Kevlar line was attached to a distributed network of Kevlar fibers spreading actuator force across the area of tendon insertion.

A custom fixture was designed to attach the leg to a load cell so that the force data could be recorded on the forefoot as plantarflexors were actuated. Pneumatic pressure of 689 kPa achieved 21.5 Nm, slightly above the goal, and 80% of the maximum moment was achieved in 98 ms (90% in 117 ms). The total ankle range of motion was determined through digital analysis of photographs and determined to be 33.5 degrees total travel in dorsi/plantarflexion (variable depending on tendon length). Similarly, inversion/eversion was measured as 18.8 degrees total travel (see Figure 10 for the neutral and flexed states).

CONCLUSIONS

Our work on the second skin suggests a set of five principles from ecological science for the design of bio-inspired soft robotic assistive devices: self-assembly, modularity, embodiment, energy sharing between neural and mechanical systems, and multifunctionality. We conclude with a brief description of how the second skin design follows each of these design principles.

Self-Assembly

Biological muscles consist of small structural units, called sarcomeres, that contract to provide a range of displacement and stiffness (Schuenke, Schulte, & Schumacher, 2010). When recruited to function collectively, they shorten or lengthen to produce or absorb energy, doing mechanical work. Muscles may also facilitate elastic energy storage and return to stabilize a joint (Higham, Biewener, & Delp, 2011). The second skin synthetic muscles, miniature pneumatic actuators, are designed to function as sarcomerelike elements so that when recruited, their collective shortening and lengthening assists the force (torque)

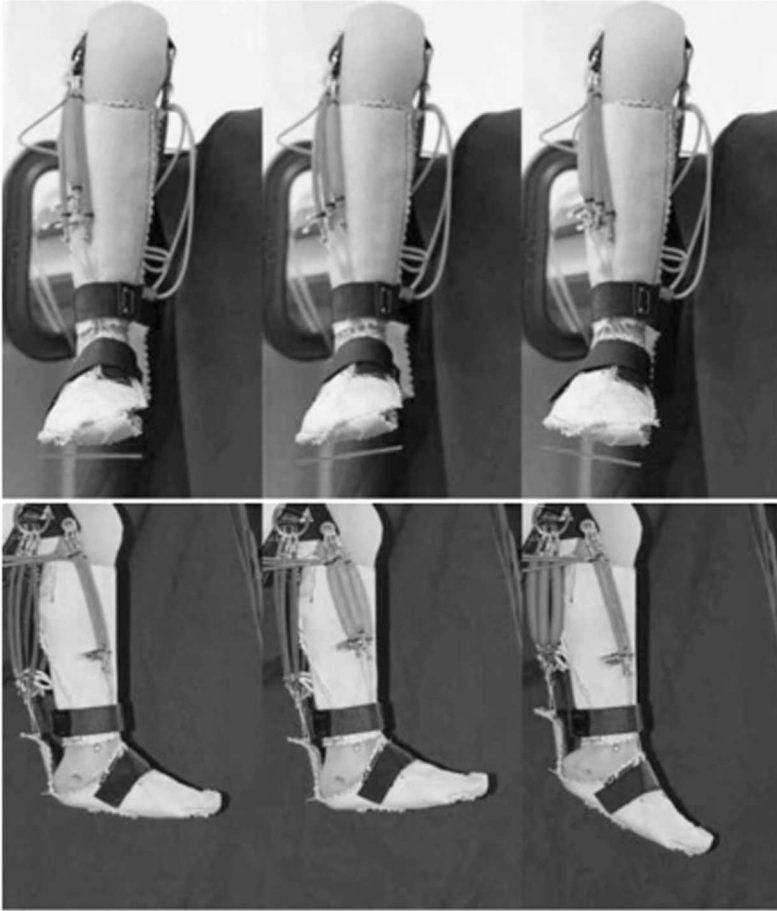


FIGURE 10 Collective contraction of second skin synthetic muscles worn on a leg model scaled to a young child produces foot inversion, eversion, dorsiflexion, and plantarflexion.

production of the biological muscles (see Ueda, Odhner, & Asada, 2007, for another approach). When arranged within fabric layers comprising a hollow cylinder worn over the skin (hence the device name, second skin), the synthetic muscles function as agonists and antagonists so that they may contract together, or contract to varying degrees on either side of a joint, to allow them to stabilize the biological limb. The design of each synthetic muscle constrains its expansion as it is filled with compressed air so that the muscle “belly” expands as its longitudinal dimension shrinks (i.e., contracts).

The second skin controllers are programmable, forming what is essentially a wearable soft robot. The robotic control system is designed according to principles from amorphous computing (Nagpal, 2002), an approach that harnesses self-assembly to form complex shapes (akin to the process of morphogenesis). Self-assembly of the second skin muscles is achieved by a leaderless election and spanning tree algorithm that detects and forms particular arrangements and degrees of muscle contractions to transform a hollow cylinder into a specific shape. To form each goal shape, the leader controller transmits a target shape to all subcontrollers, following the minimal spanning tree topology.

The synthetic muscles are a component of a functional unit that incorporates a new type of hyperelastic strain sensor, a form of flexible electronics. Each muscle is surrounded by a strain sensor, providing a bio-inspired (Golgi-tendon and spindlelike) means of feedback for detecting the contractile state of the synthetic muscle. With formation of each goal shape, the collective strain sensor output is transmitted via a sophisticated wireless network, forming a strain field specifying the contribution of the synthetic muscles across the cylindrical surface of the second skin device. It is the pattern of synthetic muscle activation, revealed in the field generated by all strain sensors, that informs the controller of the contribution of the synthetic muscles. The synthetic muscles, sensors, electrical power, compressed air supply, and microchip controller constitute a functional module with which recruitment is made possible.

Modularity

The second skin architecture consists of axially repeated modular units (sensors, actuators, and controllers) organized spatially to reflect the underlying musculo-tendon segmental anatomy. So, for example, the spatial arrangement of a second skin device worn over the wrist and forearm consists of synthetic muscles above the wrist that cooperate as one set of functional modules for bending at the wrist and a second collection of synthetic muscles that function together to open and close the hand. By contrast, synthetic muscles spanning the knee and ankle joints function together so that many different joint angle combinations may be used to maintain relatively invariant whole-limb kinematics, such as hip-ankle length. Each synthetic muscle may potentially participate in multiple modules but is constrained by the controllers to participate in certain task-specific modules associated with the underlying body anatomy (e.g., reach and grasp by the hands, walking by the legs).

Embodiment

Current wearable exoskeletal robots for assistance and neurorehabilitation are built around rigid bonelike segments connected by mechanical joints and springs.

These exoskeletons may be part of large, clinic-based, sessile robotic trainers, such as Lokomat (Cajigas et al., 2010), or are bracelike rigid orthotic devices (Lewis & Ferris, 2011). The second skin is a wearable robot with an embodied form factor: a soft, hollow cylinder with actively controlled synthetic muscles, sensors, and controllers embedded within fabric layers that conform to the tapered cylindrical forms of body segments. The biological inspiration for this alternative design is soft-bodied creatures such as worms or caterpillars. A soft-bodied form factor is well suited to an embodied network, a dense array of strain sensors and inertial measurement units embedded within each module that communicates information about the body, the second skin, and the environment. The compliance of the second skin, as its flexible shape conforms to the body, allows it to harness the rigidity of the biological skeleton, much as a caterpillar assumes the form of the substrate to which it attaches itself.

Energy Sharing Between Neural and Mechanical Systems

The second skin is an interface between biological structures and the forces impinging on and generated by the body. It is a system of components embedded within a fabric that is both passively and actively tuned. Embedded channels filled with liquid metal, flexible electronic circuits, enable the fabric to stretch and bend without damaging the circuitry. Some of the channels are patterned topologically to reflect the lines of force generated across the skin surface of the underlying anatomy, whereas others are connected into “struts and strings,” forming an equilibrium between compression of struts and tension of strings. This creates a network of mechanical elements for a kind of “preflexive” level of control. The channels may also be used for active stiffening and relaxing so that the fabric is in a state of prestress stability, inspired by mechanotransduction in nature. Thus, like the body’s tendon network, the patterning of second skin circuits creates a tuned structure that is modulated with respect to the ongoing dynamics of the body.

The second skin interface is a robotic system designed to tune the mechanical properties of the component material in a way that releases stored potential energy relative to ongoing body dynamics and minimizes the synthetic muscle energy expenditure. We are currently exploring different designs for a sensor-tuned interface, such as one that uses the mechanical resonances of each body segment for modulating energy storage and release.

Multifunctionality

The local controllers are connected by means of a wireless network that may accept different computer programs so that the same second skin modules may

become functionally reorganized for different modes of behavior. The sheet of second skin material is wrapped around the tapered cylindrical segments of the body, emulating the topological transformation during embryogenesis by which an initial sheet of cells forms a hollow cylinder. The cylinder is placed over at least two contiguous body segments, spanning one or more joints (e.g., arm segments spanning the elbow, leg segments spanning the knee, or torso and leg segments spanning the hip joint), and is able to either passively or actively bend at the joint without damaging any of its electronic components. The means for reconfiguration is to provide each module with the same initial computer program and then allow the modules, through body motion, to self-assemble by discovering how to work collaboratively to form functional modules.

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