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A Hybrid Anchoring Technology Composed of Reinforced Flexible Shells for a Knee Unloading Exosuit

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Abstract

Soft robotic wearables have emerged as an ergonomic alternative to rigid robotic wearables, commonly utilizing tension-based actuation systems. However, their soft structure's natural tendency to buckle limits their use for compression bearing applications. This study presents reinforced flexible shell (RFS) anchoring, a compliant, low-profile, ergonomic wearable platform capable of high compression resistance. RFS anchors are fabricated with soft and semirigid materials that typically buckle under compressive loads. Buckling is overcome using the wearer's leg as a support structure, reinforcing the shells with straps, and minimizing the space between the shells and the wearer's skin—enabling force transmission orders of magnitude larger. RFS anchoring performance was evaluated comparatively by examining the shift-deformation profiles of three identically designed braces fabricated with different materials: rigid, strapped RFS, and unstrapped RFS. The unstrapped RFS severely deformed before 200 N of force could be applied. The strapped RFS successfully supported 200 N of force and exhibited a nearly identical transient shift-deformation profile with the rigid brace condition. RFS anchoring technology was applied to a compression-resistant hybrid exosuit, Exo-Unloader, for knee osteoarthritis. Exo-Unloader utilizes a tendon-driven linear sliding actuation system that unloads the medial and lateral compartments of the knee. Exo-Unloader can deliver 200 N of unloading force without deforming, as indicted by its similar transient shift-deformation profile with a rigid unloader baseline. Although rigid braces effectively withstand and transmit high compressive loads, they lack compliance; RFS anchoring technology expands the application of soft and flexible materials to compression-based wearable assistive systems.

Keywords: Exosuit, wearable robot, knee brace, soft robot, thermoformable material, customization

Introduction

Robotic wearables have become a staple of modern human assistive technology, designed to augment and assist human locomotion. Assistance by these systems is achieved by manipulating the wearer's body with force generated by the system's actuators; this force is transmitted to the wearer's body through worn components that commonly take the form of rigid frames or textile clothing, referred to as *anchoring systems*. Anchoring systems play a critical role in the wearable robot's ability to transmit sufficient force to the wearer, since force transmission cannot occur if an anchor is improperly adhered to the body, deforms, or separates from the body.

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Since the position and direction of forces applied by an actuator to an anchor depend on the wearable robot application, anchoring systems must be carefully designed. Rigid robotic exoskeletons typically fix anchoring systems composed of rigid frames to the wearer's body and transmit actuator force normal to the surface of the body to push or pull the limb.[1,2] Soft exosuits tie lasso-like straps to an anchoring system to transmit tension to the body, by pulling the straps with a wire longitudinally from the anchor surface.[3–9] These conventional methods have generally only been applied to anchoring systems for wearable robots that assist joint rotation. In particular, research into the application of soft anchoring systems for wearable devices that relieve joint compression are missing, since the inherent softness of these systems limits their ability to bear compressive forces.

Developing a soft anchoring system to relieve joint compression requires knowledge about how current joint-unloading wearables function. Unloading devices for knee osteoarthritis (KOA) patients are the most representative systems that relieve knee joint compression. Since nearly two to three times an individual's bodyweight is applied to the knee during walking,[10] traditionally, individuals with KOA would rely on the assistance of some rigid external support like a cane to offload a portion of their bodyweight.[11]

As understanding of KOA increased, designers created wearable braces that were meant to mimic these devices like unicompartmental[12,13] and multicompartmental[14,15] knee braces. Unloader braces achieve knee unloading by transmitting pushing forces or moments generated by functional joint mechanisms to anchors, fixed at the thigh and shank, that are rigid enough to withstand the mechanisms' large compressive forces.[16,17] Therefore, it is very challenging for KOA braces to fabricate their anchoring systems with soft materials because of their poor compression resistance. At the same time, some individuals with KOA want alternatives to rigid knee braces because they are heavy, inflexible, and bulky.

An advantage of soft robotic wearable devices is their ability to take on the shape of their current wearer. Still, this is a consequence of soft robotic wearables' inability to resist external forces or maintain shape on their own; the performance of these systems is predominantly determined by how effectively their anchoring systems utilize the wearer's body as a support structure for reinforcement and force transmission. Exo-Glove, a tendon-driven soft robotic glove, rerouted its tendon path to reinforce the glove with the wearer's fingertip—reducing fingertip force transmission losses caused by the stretching and deformation of the glove's fingers.[3] An exosuit developed by Harvard University introduced the concept of virtual anchoring, a network of ideal anchoring locations that are good at supporting loads and have high stiffness, like the foot and pelvis.[4] By placing anchors at these locations, the exosuit is strongly reinforced and capable of distributing high actuator forces.

Improved force distribution by exosuits onto the body has also become a focus of researchers. In a separate study conducted at Harvard, researchers investigated the benefits of Y-shaped waist strap attachments fabricated using various stiffness textiles, utilizing the pelvis for reinforcement while avoiding points of high pressure that may cause discomfort or restrict blood flow.[5–7] At Vanderbilt University, a custom-molded semirigid outer shell was attached to the surface of an elastomer gel shank sleeve to redistribute forces and reinforce the sleeve.[8] Exo-Wrist, a corset-inspired active forearm anchoring sleeve, found that various actuator forces could be supported by controlling the tightness of their anchor with a motor depending on the desired application.[9]

It is important to note that all of the aforementioned systems reinforced the soft materials of their anchoring systems beyond their original strength to support tensile forces from actuators. One study designed a soft wearable robotic ankle-foot orthosis with the capability to resist compressive forces caused by a motor on the ankle joint.[18] An incompressible semirigid beam was incorporated into their anchoring system, but the semirigid beam was unreinforced. Semirigid materials that are usually incorporated into soft wearables normally buckle under compressive loads higher than the materials' load-bearing capacity. Reinforcement techniques have enabled soft anchoring systems to transmit tensile forces to various regions of the body; however, the reinforcement of soft materials on their own has still proven to be ineffective for anchoring systems that must bear and transmit compression forces. Therefore, new compression-resistant soft anchoring technologies are necessary that can expand the achievable ergonomic applications of soft wearables.

This study presents reinforced flexible shell (RFS) anchoring, a soft and semirigid hybrid force transmission technology with the ergonomic sensibilities of soft wearables, but with the compressive load transmission capabilities of rigid wearables (Fig. 1E–H). By constraining the flexion of RFS anchor's semirigid materials along their transverse axis with straps, using the wearer's leg as a support structure, RFS anchors can withstand and transmit compressive forces' orders of magnitude larger. When compressive force is applied to an RFS anchor the semirigid regions do not deform, instead distribute applied force over the anchor's entire area.

To showcase one of the possible applications of RFS anchoring, *Exo-Unloader*, a compliant material-based knee unloading exosuit, was developed (Fig. 1A–D). Unloading forces generated by tendon-driven linear sliding (TDLS) actuators are transmitted by Exo-Unloader's RFS anchoring by pushing proximally on the wearer's thigh and distally on the wearer's shank. The wearer's thighs and shanks are fitted with RFS anchors customized to the wearer's body.

RFS anchors are fabricated by combining textile-like thermoplastic fabric and stretchable textiles; thermoplastic fabric is patterned and placed where compressive actuator forces need to be transmitted and redistributed to the body. Before molding, thermoplastic fabric works and feels like any other soft stretchable fabric, making it easily incorporable into traditional cut and sew textile fabrication processes. This unique technique enables an RFS anchor's soft and semirigid materials to be quickly customized to perfectly fit to individual wearers. RFS anchoring and TDLS actuation technologies' compliance enables more natural motion by the wearer, while the suit remains well-fit to the body (Supplementary Movie S1). Currently, Exo-Unloader is designed to deliver 200 N of unloading force, comparable with the assistive force supplied by conventional unloading braces[16,17] and canes.[11]

RFS Anchoring

RFS anchoring design and fabrication

For Exo-Unloader to function effectively, the suit must be designed so it can adhere to the thigh and shank with minimal

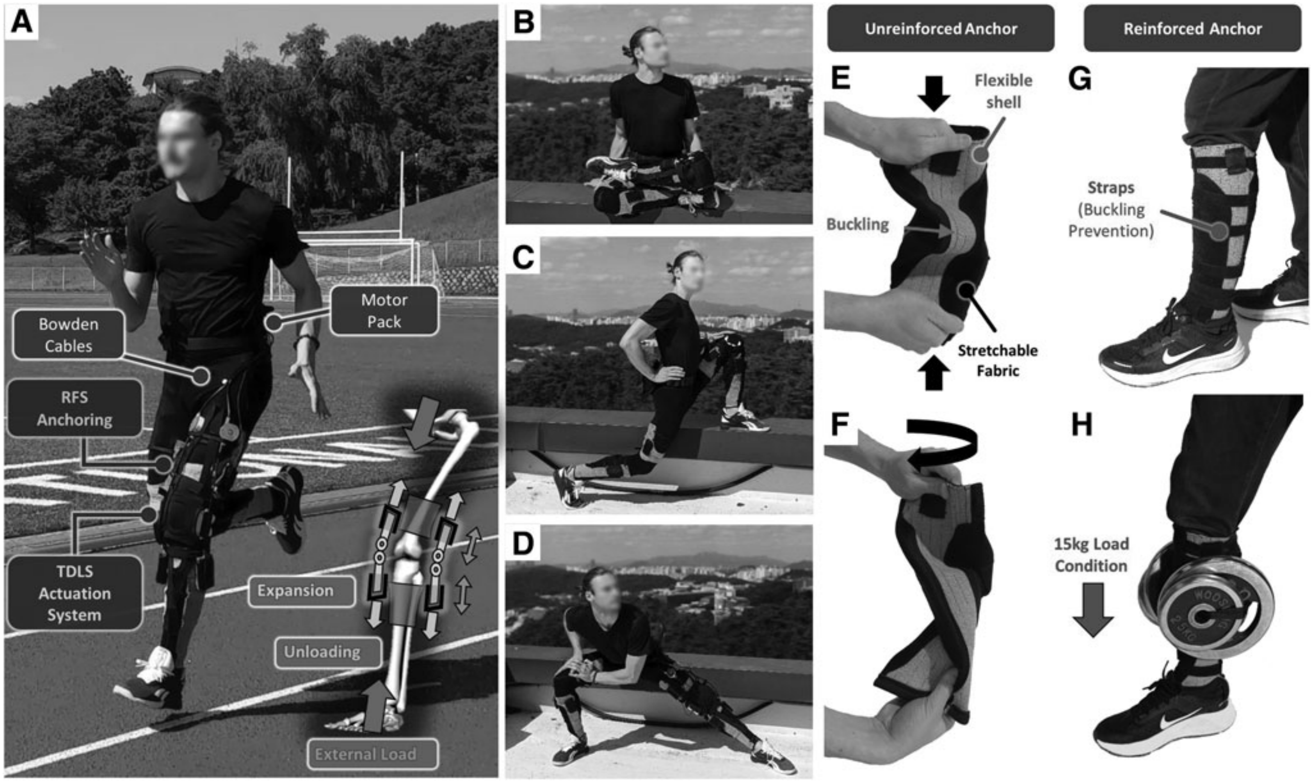

FIG. 1. Exo-Unloader, a compression-resistant hybrid exosuit fabricated with RFS anchoring technology, designed to unload the wearer's knee. **(A)** Exo-Unloader worn while a subject sprints on a track (Supplementary Movie S1)—unloading is achieved using two TDLS actuators attached to the medial and lateral sides of the knee. Exo-Unloader's soft and semirigid materials allow wearers to assume a variety of postures typically restricted by wearable devices like: **(B)** cross-legged lotus, **(C)** forward lunging, and **(D)** sideways lunging. RFS anchors are the combination of soft stretchable fabric and semirigid thermoplastic fabric, easily **(E)** buckling and **(F)** twisting under external loads. **(G)** When reinforced with straps against a wearer's limb, **(H)** RFS anchors are capable of bearing compressive loads with orders of magnitude larger while still remaining closely fit to the wearer's body. RFS, reinforced flexible shell; TDLS, tendon-driven linear sliding.

deformation and slip, *anchoring*. Properly designed anchoring technology can maximize the force transmitted to the body; RFS anchoring technology enables Exo-Unloader to effectively transmit forces proximally to the thigh and distally to the shank.

RFS anchoring is a hybrid force transmission technology enhanced by the fusion of two or more compliant materials into a single garment. In Exo-Unloader, RFS anchoring is composed of two different materials: semirigid thermoplastic and soft stretchable fabric. Semirigid thermoplastic is patterned and placed where actuator forces need to be transmitted to the body. The rest of the suit consists of stretchable fabric that works in conjunction with thermoplastic regions to form a well-fitted anchor.

Conventional soft anchors resist longitudinally applied tensile forces from actuators with lasso-like straps. However, these materials cannot withstand compression, only regions of the textile that act in tension against the applied force can support the load, while areas in compression buckle and deform, limiting the area of the anchor that can be recruited to support the load (Fig. 2A). Similar to soft materials, semirigid materials can also buckle away from the body's surface. RFS anchoring resolves this by reinforcing semirigid materials against target areas of the body with inextensible straps. RFS anchors' semirigid materials distribute force through the entire anchor, recruiting all fastened reinforcing textiles to tighten and prevent deformation.

Semirigid sections of the anchor can then endure large compressive forces without yielding and can recruit the entire area of the anchor to support and resist external forces regardless of application point (Fig. 2B). Depending on where RFS anchoring is worn, force distribution will differ as demonstrated in Figure 2C–E. Since semirigid RFS anchoring sections are inherently compliant, they mold perfectly to the curvature of the body. RFS anchoring's compliance before it is worn, and its strong resistance to compression forces after it is worn, is demonstrated in Figure 1E–H.

RFS anchors are designed for user customization; they can be readily fabricated with any thermoformable material. In this study, RFS anchors were fabricated by combining textile-like thermoplastic fabric (Orficast,unmolded thickness of 2.5 mm; activation temperature of 65°C; Orfit, Belgium) with stretchable fabric to create the base of the suit (Fig. 3A). Before it is molded, thermoplastic fabric works and feels like any other stretchable fabric (Fig. 3B–D). Thermoplastic fabric's initially soft stretchable state makes it easy to incorporate into traditional cut and sew textile fabrication processes, ideal for textile applications. For this study's RFS anchoring design, thermoplastic fabric was combined using cut and sew techniques with soft stretchable fabric to make a

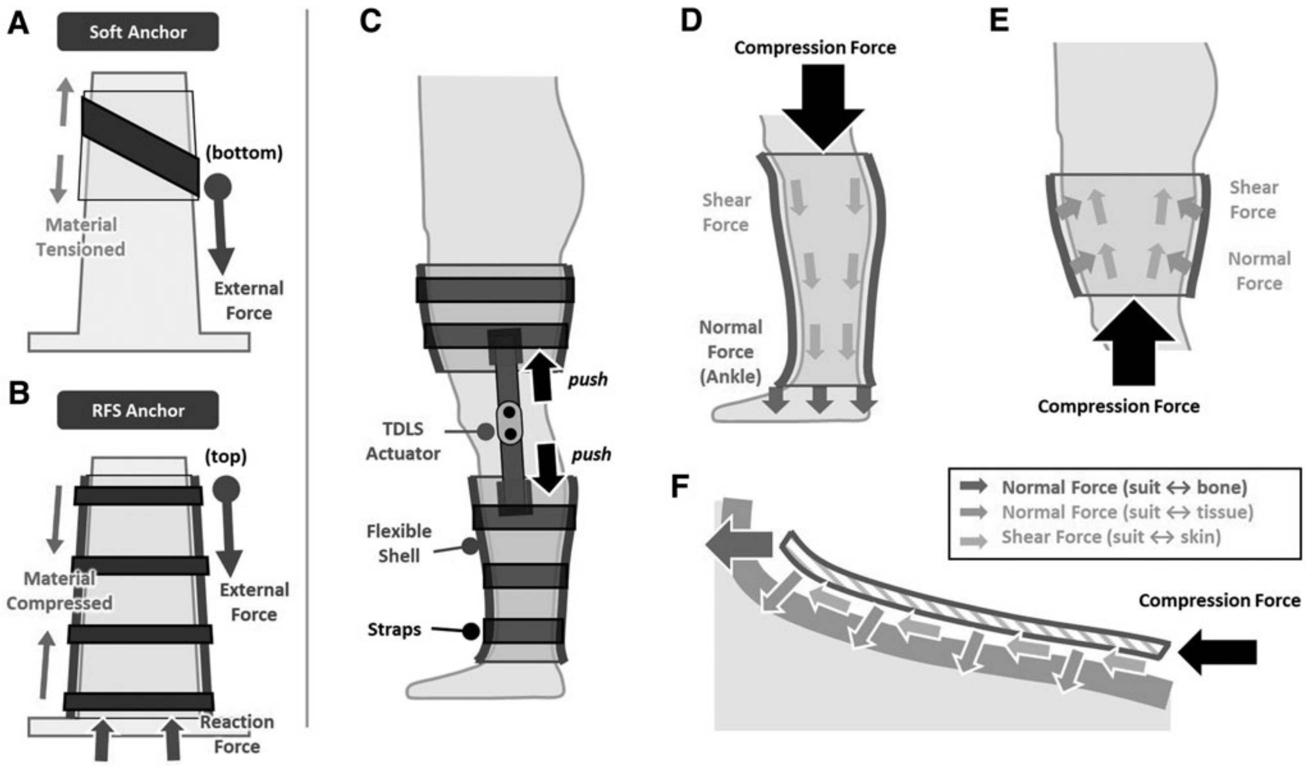

FIG. 2. RFS anchoring principles and its application to Exo-Unloader. **(A)** A conventional soft anchor—tensile forces must be applied from the leading edge of the textile, where only regions in tension resist the force while regions in compression buckle and deform. This limits soft anchors' effective recruited anchoring area, only permits tensile load resistance, and limits the locations where these forces can be applied. **(B)** An RFS anchor—when force is applied to the anchor, all semirigid regions of the anchor are recruited to resist the force, evenly distributing the load over its entire area. Straps assist in force distribution and prevent buckling of the semirigid regions, allowing RFS anchors to support compressive loads. **(C)** Exo-Unloader is the combination of RFS anchoring and two TDLS actuators fixed to the medial and lateral surfaces of the thigh and shank. In RFS anchors, force distribution to the body is dependent on the region that the anchor is located, like in the case of the **(B)** shank and **(C)** thigh. **(D–F)** When external compression forces are applied to an RFS anchor—the anchor acts as a conduit, redistributing the force as shear and or normal force to the skin and underlying tissue, or as normal force to nearby bony structures in contact with the anchor.

pair of well-fitted pants for various body segments and sizes (Supplementary Fig. S2). Sample patterns are available in Supplementary Figure S4.

Once fabricated, RFS anchor pants can then be heated and molded to their designated wearer. These pants were heated using a 65°C heated water bath, slightly cooled to prevent wearer discomfort, and then shaped to the wearer's body (Fig. 3E, F). Once completely cool, thermoplastic fabric retains its new molded shape and adopts semirigid material properties. Molded thermoplastic fabric can be reshaped by reapplying heat, softening the material, and allowing recustomization to another wearer. Designers can easily modulate the stiffness of the thermoplastic fabric by applying additional heat, pressure, and or layers for a wearable's specific design parameters. This customization process not only increases comfort for wearers but also improves reinforceability and buckling risk by minimizing the space between the wearer's skin and the flexible shell.

RFS buckling simulation

Before RFS anchor experiments were conducted a buckling simulation (SOLIDWORKS, Dassault Systèmes SE, France) was performed on a rectangular sample (Material = Nylon 101, $H = 300$ mm, $W = 50$ mm, $T = 2.5$ mm, 100 N vertical load) meant to represent the simplified version of a medial RFS shank anchor component to provide a design guideline for readers (Fig. 4A). The simulation's reported Buckling Factor of Safety (BFS) must be larger than 1 to prevent buckling under the defined loading conditions. The BFS was evaluated as strap number ($W = 25$ mm) on the sample was changed between 0 and 5 straps to visualize their trend. The 1-strap condition was not assessed since it does not reflect a realistic design choice. The 0-strap condition represents an unreinforced anchor. An increase in buckling resistance occurs as strap number increases (Fig. 4B), which was then verified in the following experiments (Fig. 4C–G).

Performance verification

An experiment was designed to verify the compressive and shift resistant abilities of RFS anchoring. All experimental procedures used in this study were approved by a Seoul National University Internal Review Board (IRB No. 2106/001-022), and subjects provided permission for the publication of their photographs for scientific purposes. To observe effects caused by differences in user physique, two subjects (Height—Subject A: 165; Subject B: 175 cm; Supplementary Table S1) were provided customized anchors.

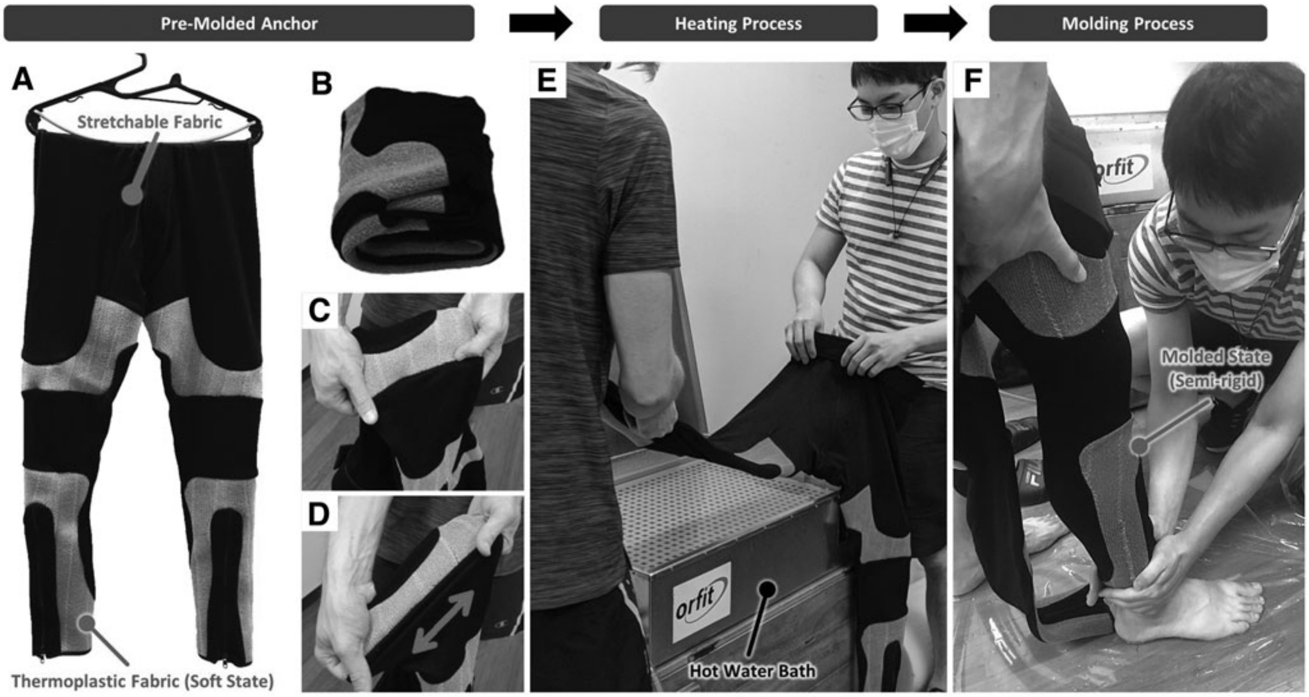

FIG. 3. Fabrication process for the RFS anchoring used in Exo-Unloader. **(A)** The anchor is first designed and fabricated using stretchable fabric and unmolded thermoplastic fabric with cut and sew techniques. **(B)** In its premolded state, RFS anchors are soft and foldable, and **(C, D)** stretchable allowing designers to fabricate them so that they can fit snugly with the wearers' body for high quality molding. Once fabricated, **(E)** the anchor is submerged in a hot water bath to enter a heated and moldable state. **(F)** Operators then mold the anchor to the wears limb, allowing time to cool and harden before removal.

The setup consisted of a motor, wires, pulleys, and a load cell, built to pull on the proximal end of an RFS shank anchor, simulating compressive loading (Fig. 5A). Wires were attached to the anchor's medial and lateral proximal sides and pulled distally toward the foot and through a pulley system. A load cell (100 kgf; K-TOYO Co. Ltd., South Korea) was attached in series with the wire, allowing tension to be recorded in real-time. Three shank anchor designs were tested using this experimental setup: (1) a rigid anchor fabricated from thick and rigid thermoplastic sheet (Orfit Classic, thickness = 2.5 mm; Orfit Industries, Belgium), (2) an RFS anchor (strapped), and (3) an RFS anchor without reinforcement straps (unstrapped).

The rigid thermoplastic anchor's dimensions were designed to match the RFS anchor's shape and size. A maximum of 200 N of force was applied to the anchors by a motor (Dynamixel Pro H54-200-S500-R, Controlled with Dynamixel Wizard 2.0; Robotis Inc., Korea) at a rate of 4.2 mm/s, and each test condition was evaluated five times (Fig. 5D–F). From the experiment's results (Fig. 5B, C), the rigid anchor shifted and deformed the least of the three test conditions at 200 N for both subjects (Average max shift—Subject A: 11.6 mm; Subject B: 8.3 mm), and the strapped RFS shifted slightly more (Average max shift—Subject A: 13.4 mm; Subject B: 8.7 mm). For both conditions shifting occurred linearly as compression force was applied. From visual observation (Fig. 5B, C), deformation of these two anchors' structure at max load appeared to be minimal.

The third testing condition demonstrated how RFS anchors perform when the semirigid sections of the system are not reinforced. Buckling and shifting occurred when compression was applied to the unstrapped RFS anchor. Once the anchor buckled, the measured distal-proximal compressive force on the shank anchor did not continue to increase past 101 N for subject A and 79.2 N for subject B as the motor pulled the wire. From the shift and deformation profiles in Figure 4, it is clear that the unstrapped condition forms a diverging profile compared to the rigid baseline condition as significant deformation began to occur. This was not exhibited in the strapped condition, even though both designs are exactly the same. The profile nearly identically matched that of the rigid baseline condition indicating that it behaved similar to a rigid anchor.

TDLS Actuators

TDLS actuator design and fabrication

A TDLS actuation system is composed of the following components: a pair of tendon-driven linear sliders and a gear joint-linkage structure (Fig. 6A–C). A low-profile pushing mechanism, a TDLS actuator, can be created by connecting two carriage systems together by a joint by thin semirigid beams. TDLS actuation is generated when a Dyneema cable connected to the actuator carriage is pulled. The motion of the linear guides on either end of the joint-linkage structure is coupled together with a pulley at the end of a Bowden-cable tendon path. Therefore, the cases on either end of the system move away from the center of the joint when the cable is pulled (Fig. 6A, B). Similar to RFS anchors, TDLS actuators are fabricated with semirigid materials (Fig. 6E, F) that buckle easily under compressive loads, but can be reinforced

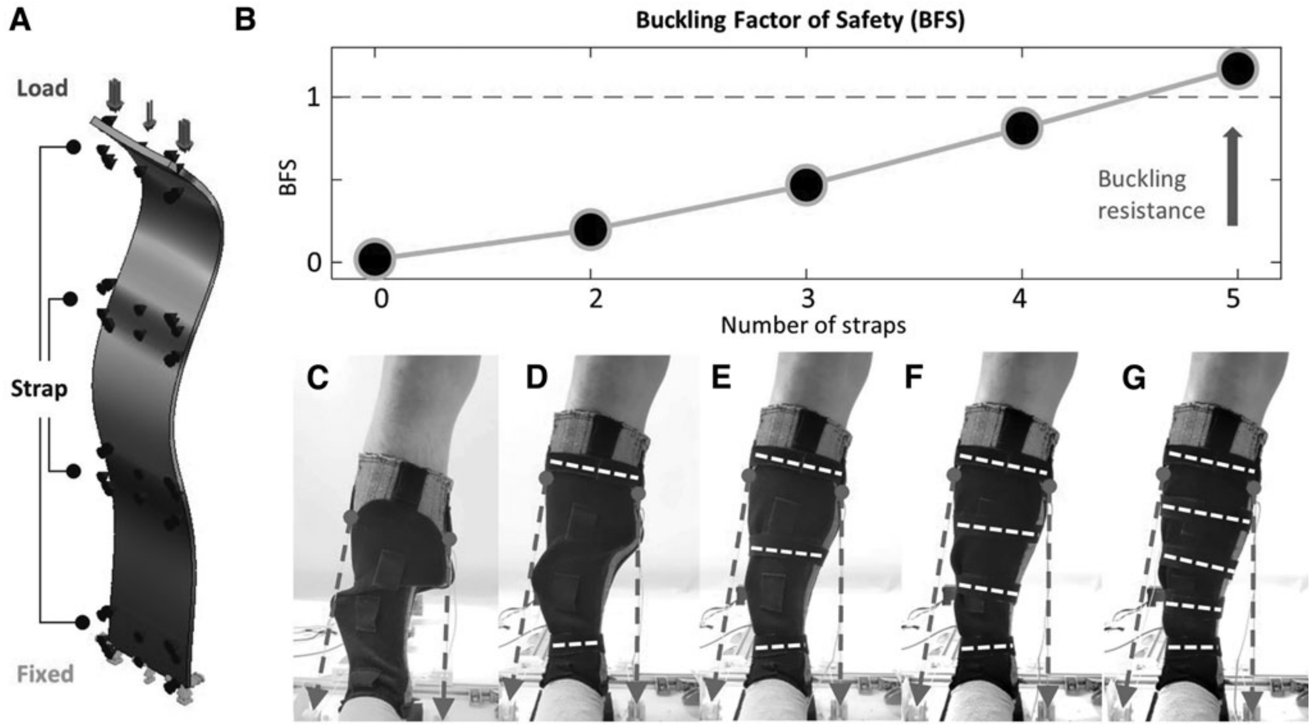

FIG. 4. Buckling simulation and strap number validation experiment. **(A)** A simplified buckling simulation performed using the SOLIDWORKS simulation tool (Dassault Systèmes SE, France) to give readers a design guideline. This simulation was run for a total of five strapping conditions: 0, 2, 3, 4, and 5 straps. **(B)** Simulation results—BFS, the ratio between the buckling load and the applied load, the BFS must be larger than one to prevent buckling under the specified loading conditions. As the number of straps increased the resistance to buckling by loading increased. While straightforward it was important to simulate some potential outcomes before conducting experiments with subjects. **(C–G)** Degree of observed buckling for the five strapping conditions when experimentally validated on Subject B. Images were captured when 200 N of force was applied, with the exception for **(C)** since the 0-strap anchoring condition buckled at 80 N of force. BFS, bucking factor of safety.

with soft straps. Their scale relative to the human leg makes them easy to integrate into a robotic knee orthosis without significant additional bulk.

Buckling prevention, strapping, and performance

TDLS actuator force transmission is highly dependent on its buckling resistance and is achievable by reinforcing the semirigid structure with modular strap inputs. An experimental setup evaluated buckling using two major conditions: an unstrapped condition and a strapped condition. A TDLS actuation system (Material = Stainless Steel, $H = 290$ mm, $W = 28$ mm, $T = 0.7$ mm) with load cell embedded joints (45 kgf; FUTEK Advanced Sensor Technology, Inc.) was installed on either side of a custom-made rigid mannequin leg made from a publicly available 3D scan (Size Korea, South Korea) with an embedded load cell (100 kgf; K-TOYO Co. Ltd.). The setup was designed to mimic the idealized strapped and unstrapped conditions of Exo-Unloader (Fig. 7A). These conditions tested the effect of strap reinforcement on actuator output force and the actuators' ability to translate force to a body.

Each condition was designed to be tested 10 times, and the actuators were actuated until the force translated to the mannequin by the actuators reached 200 N or until the condition began to buckle. The strapped condition successfully translated 200 N of force (average TDLS actuator force = 192 N; average motor force = 135 N) to the mannequin when without buckling (Fig. 7B, E). The unstrapped condition translated an average of 122 N of force before buckling occurred (average TDLS actuator force = 112 N; average motor force = 80 N), and could only be tested five times due to permanent deformation from fatigue (Fig. 7C, F). Reinforcing the semirigid components of the TDLS actuation system can maintain low-profile design without sacrificing unloading capabilities. This experiment also confirmed that the TDLS actuator load cells are a reasonable indicator of the forces that would be transmitted to a wearer.

Exo-Unloader

Integrated system design

Exo-Unloader showcases the abilities of RFS anchoring when combined with TDLS actuation technology. Exo-Unloader is an unloader orthosis targeted for KOA patients to reduce the compressive forces experienced by the medial and lateral compartments of the knee. Unloading is achieved by equipping two TDLS actuation systems to the medial and lateral sides of Exo-Unloader's RFS anchoring system. The RFS anchoring system transfers TDLS actuator force to the body; compressive force is distributed to the thigh and shank.

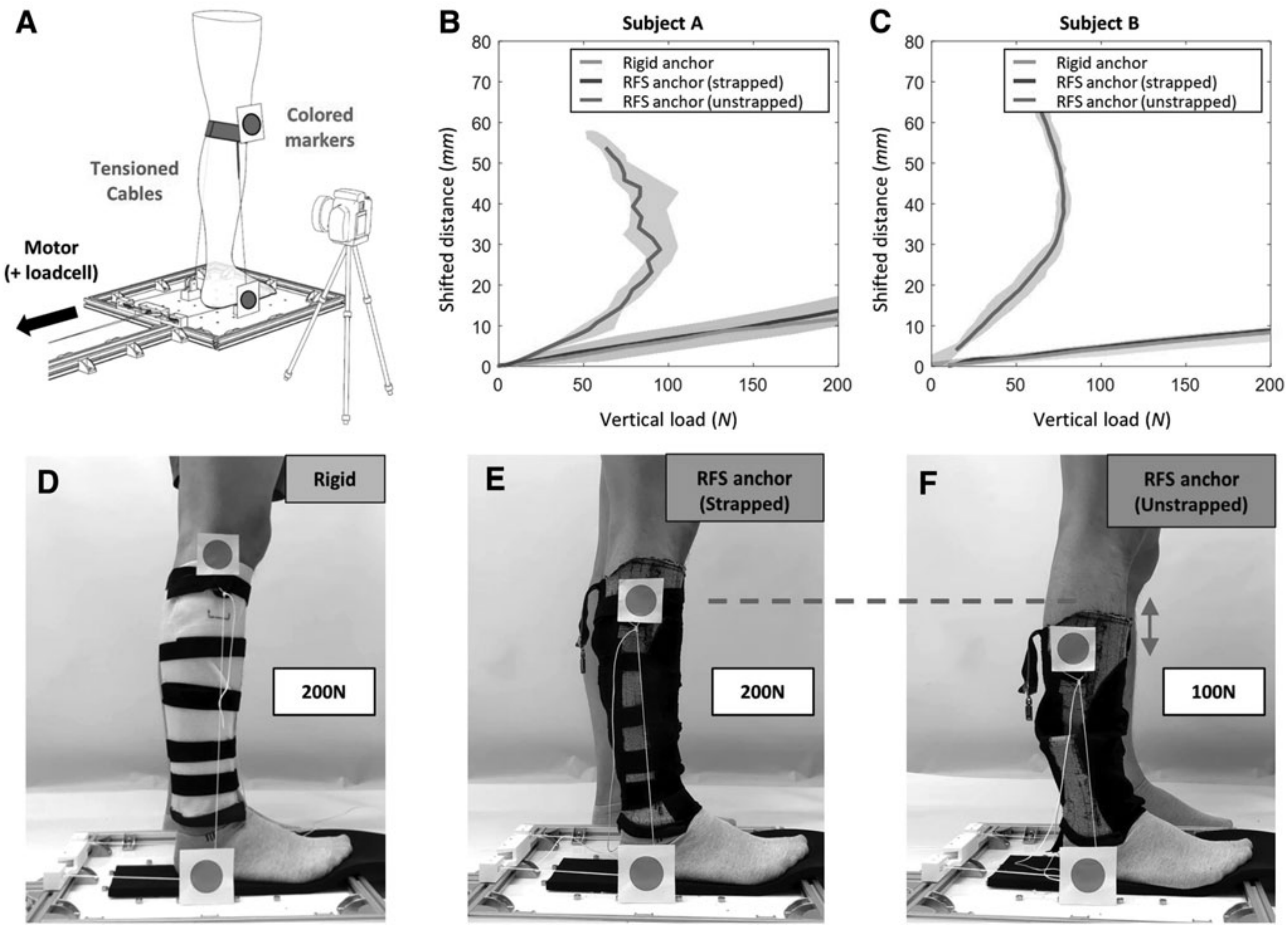

FIG. 5. Experiment evaluating the anchoring capabilities of RFS anchoring technology. **(A)** A subject was asked to stand in the experimental setup while wearing one of three shank anchoring conditions: a rigid anchor, a strapped RFS anchor, or an unstrapped RFS anchor. A maximum of 200 N of force was applied to all three conditions, and the results of these experiments are reported for subject A in **(B)** and subject B in **(C)**. Compared to the baseline custom-made rigid anchor **(D)**, the strapped RFS anchoring condition **(E)** shifted up to 16% more of the baseline, and the unstrapped RFS anchoring condition **(F)** failed before maximum force could be applied (100 N). The relative position of the markers attached to the shank anchor and base of the experimental setup, during actuation, was recorded using a camcorder and measured using MATLAB's image processing toolbox.

Exo-Unloader's RFS technology is the fusion of two primary material types: semirigid molded thermoplastic and soft stretchable fabric. Semirigid regions of the suit are patterned to deliver and redistribute the compressive forces from the TDLS actuators to the body without deforming or slipping. The remaining regions of the suit are fabricated using stretchable fabric, maintaining a snug fit with the wearer's body and reinforcing the semirigid regions of the suit against deformation and buckling. Reinforcement straps are incorporated to prevent load-bearing regions from deforming or buckling.

TDLS actuation systems were fixed to Exo-Unloader using pockets. Each TDLS actuation system is tethered by Bowden cables to a centralized gearbox and pulley mechanism attached to a motor (Dynamixel Pro H54-200-S500-R; Robotis, Inc., Republic of Korea). This synchronizes the medial and lateral TDLS actuation systems, ensuring that a uniform unloading force is applied. The cable tension is theoretically amplified by 1.5 times in the course of transfer to the TDLS. The full motor-gearbox-pulley system is contained with lithium-polymer batteries in a small waist pack situated on the wearer's back (Supplementary Fig. S1). Instructions on how to wear the Exo-Unloader are explained and demonstrated in Supplementary Figure S3.

Exo-Unloader performance

Two subjects (Height—Subject A: 165; Subject C: 178 cm; Supplementary Table S1) were provided customized Exo-Unloaders and custom rigid unloader systems of similar design. Shift and deformation of the two devices were compared when loaded by two TDLS actuators medially and laterally attached to the leg (Fig. 8B, C). Actuator-generated force on both sides of the knee was measured with load cells (45 kgf; FUTEK Advanced Sensor Technology, Inc.) installed into the joints (Fig. 6C), and each device was tested up to 200 N of unloading force five times.

Shifting of the devices was calculated by tracking the motion of markers attached at the thigh, knee, and shank using software (image processing toolbox, MATLAB; MathWorks). Combined thigh and shank shifting and

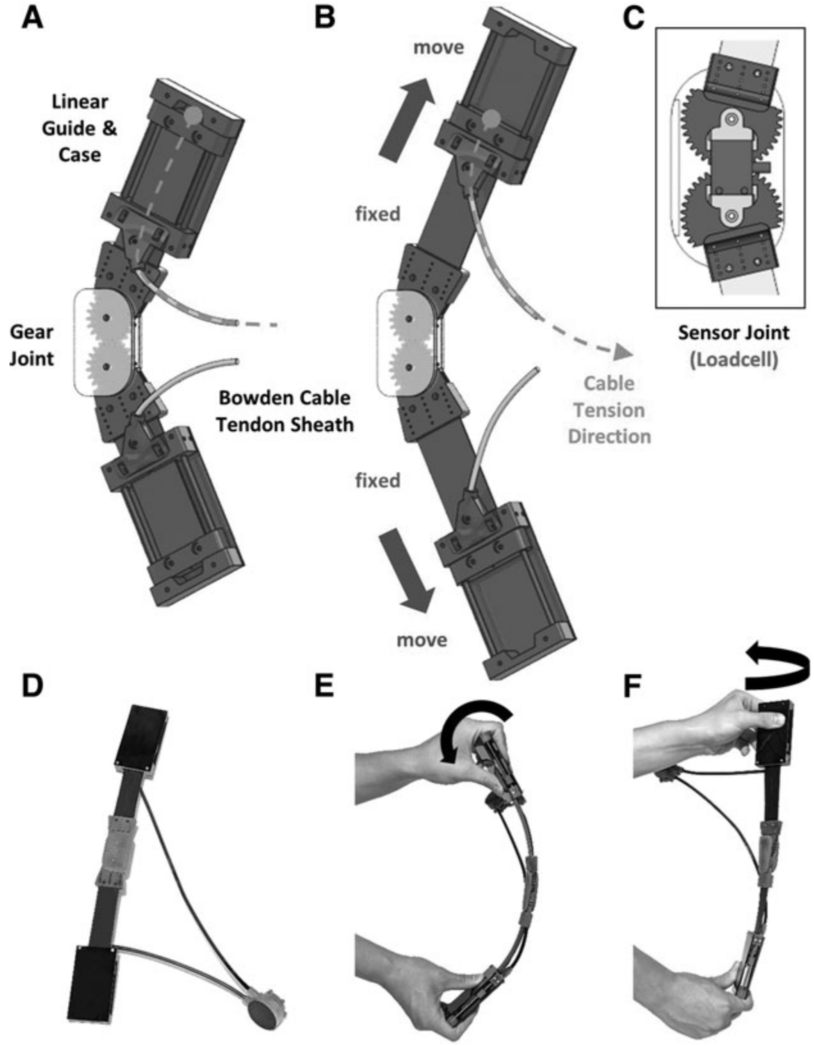

FIG. 6. A TDLS actuator. **(A, B)** When tension is applied to the Bowden cables attached to both linear guides, the cases move outward relative to the guides, resulting in total expansion of the system. When a TDLS actuator is constrained from expanding, **(C)** the resulting compressive forces applied to the central gear joint can be measured using an embedded load cell. **(D)** TDLS actuators can be either actively or passive controlled, and their semirigid design enables **(E)** bending and **(F)** twisting.

deformation for the Exo-Unloaders and rigid unloader systems are reported in Figure 8E and F. At $\approx$200 N of unloading force a minimum–maximum shifting spread of $\approx$40–43 mm for subject A and $\approx$32–42 mm for subject C was observed. For the rigid unloader system, $\approx$200 N of combined unloading force resulted in an observable minimum–maximum shifting spread of $\approx$26–28 mm for subject A and $\approx$29–35 mm for subject C. As was discussed in Reinforced Flexible Shell Anchoring section, when RFS anchors exhibit transient profiles similar to their rigid baseline it can be concluded that their force transmission behaviors are similar. Based on the profiles shown in Figure 8 this can be reasonably concluded.

Discussion and Conclusion

This introduces and presents RFS anchoring, a soft and semirigid hybrid force transmission technology with the ergonomic sensibilities of soft wearables, but with the compressive load transmission capabilities of rigid wearables. By constraining the transverse axis of RFS anchor's semirigid materials and using the wearer's leg as a support structure to reinforce the shells, the transmission of compression forces orders of magnitude larger is possible. To showcase one of the possible applications of RFS anchoring, *Exo-Unloader*, a compliant material-based knee unloading exosuit was developed by incorporating TDLS actuators.

Braces for KOA are one example of an application where soft alternatives have been unable to replicate the functions of conventional rigid KOA knee braces. Exo-Unloader is presented as a softer alternative to current rigid bracing devices. Exo-Unloader's TDLS actuators unload the medial and lateral compartments of the knee using semirigid flexible beams. By design, RFS anchoring purely supports compression forces without constraining the leg or restricting movement in other planes. In addition, the semirigid and soft materials that make up RFS anchoring technology can adaptably match to the shape of a wearer's body even as their body posture changes. Exo-Unloader also enables wearers to comfortably assume a variety of postures used in daily life that are generally taken for granted, like an individual crossing their legs.

During walking the knee joint experiences force up to two to three times bodyweight.[10] Research into well-established KOA-assistive devices like canes and braces has indicated their capability to reduce gait compression: 1.9–8.4% for canes,[11] and 7–25% for medial compartmental braces.[16,17] When assuming a 70 kg wearer, supporting 200 N of force is comparable with the support of these devices. RFS

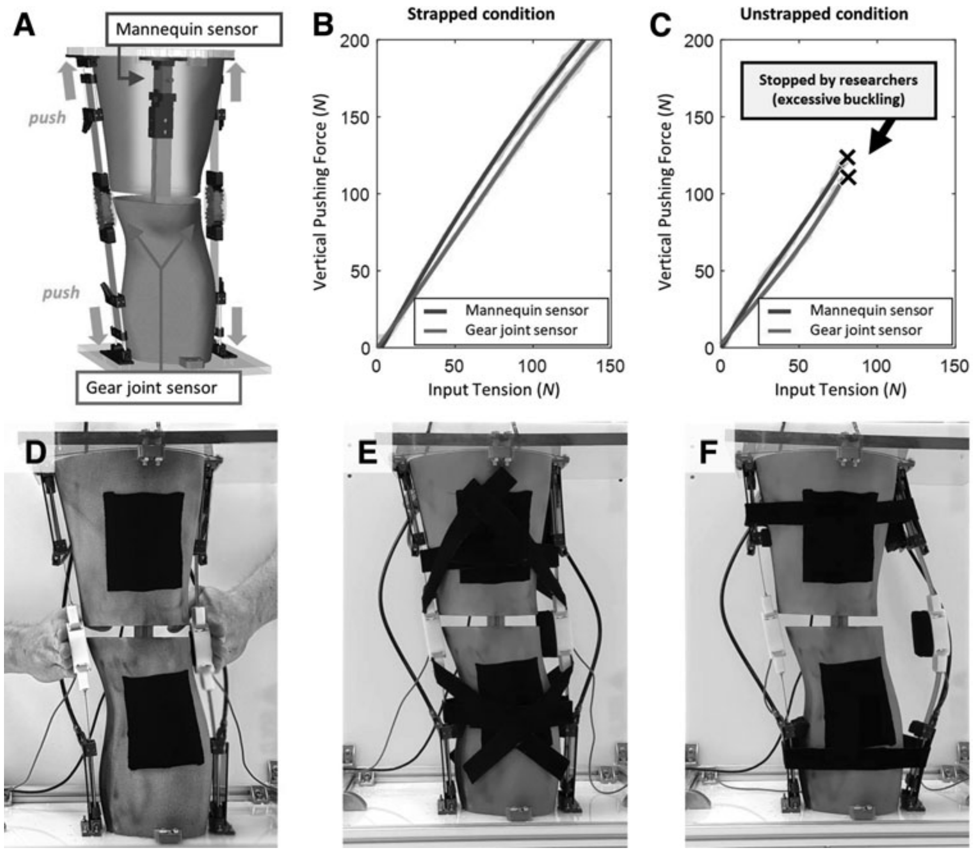

FIG. 7. An experiment evaluating the pushing capabilities of TDLS actuators. **(A)** The relative unloading capabilities of TDLS actuators in either their strapped or unstrapped state were compared using an experimental setup simulating a wearer's leg. Two actuators fixed to the top and bottom of a mannequin leg were actuated using an off-board motor-control system. The results for the strapped condition are reported in **(B)** and for the unstrapped condition in **(C)**. The actuators compliant nature and ability to conform to the body are demonstrated in **(D)**. The strapped condition mimicking the condition that would be used for the Exo-Unloader are shown in **(E)**, followed by the consequences of not properly strapping the TDLS actuation system demonstrated by **(F)**. Both conditions were actuated until the mannequin load sensor reached 200 N; however, the unstrapped condition was stopped at 100 N due to excessive buckling.

anchoring, TDLS actuator, and Exo-Unloader technologies were tested against this benchmark as demonstrated in the experiments presented in sections 2, 3, and 4 of this article, exemplifying the potential of hybrid systems for compression force support applications.

Misalignment between a brace and a wearer's knee has the potential to generate spurious contact forces.[19–21] Exo-Unloader's alignment with a wearer's knee during use has not been evaluated; in future work, the degree of misalignment between Exo-Unloader and wearers will be taken into consideration, with the design of a new mechanical joint to minimize these effects. Evaluations of Exo-Unloader's performance were limited to standing conditions. Therefore, the magnitude and profile of Exo-Unloader's unloading force are currently not controlled as desired during walking or running. To utilize Exo-Unloader during activities of daily living (ADLs), the following studies are required: (1) a parametric study of RFS anchoring, (2) development of a motor for and speed optimization control strategy, and (3) development of a new sensing method for knee loads that is reliable for various knee angles.

In this study RFS anchoring and Exo-Unloader were both tested on two subjects who differed in height by >10 cm (Supplementary Table S1). This provided preliminary insight into the scalability of RFS anchoring, TDLS actuators, and Exo-Unloader to various subjects. However, experiments with a larger set of subjects varying in weight, height, gender, and age are necessary to fully evaluate the capabilities of these technologies. Future studies will also consider the need for evaluation of these technologies during different ADLs to comprehensively understand its impact on wearer quality of life and behaviors.

RFS anchoring technology's applications are not limited to just knee bracing, and the fabrication techniques highlighted in this study can be easily applied to various soft wearable robotic systems. Existing soft robotic anchors are only capable of bearing tensile stresses. Therefore, they are constrained to interfacing with actuators that apply tensile forces limiting their design degrees of freedom (DOFs) and application to optimal designs. In addition, only limited regions of a soft anchor are recruited to support an applied load, creating pressure concentrations that can result in discomfort and pain. RFS anchoring technology addresses these limitations, widening the design DOFs of soft and compliant materials, enhancing them with the ability to bear compressive loads: improving force distribution and enabling the free application of force anywhere on the device without sacrificing comfort. RFS anchoring technology will be applied to various soft

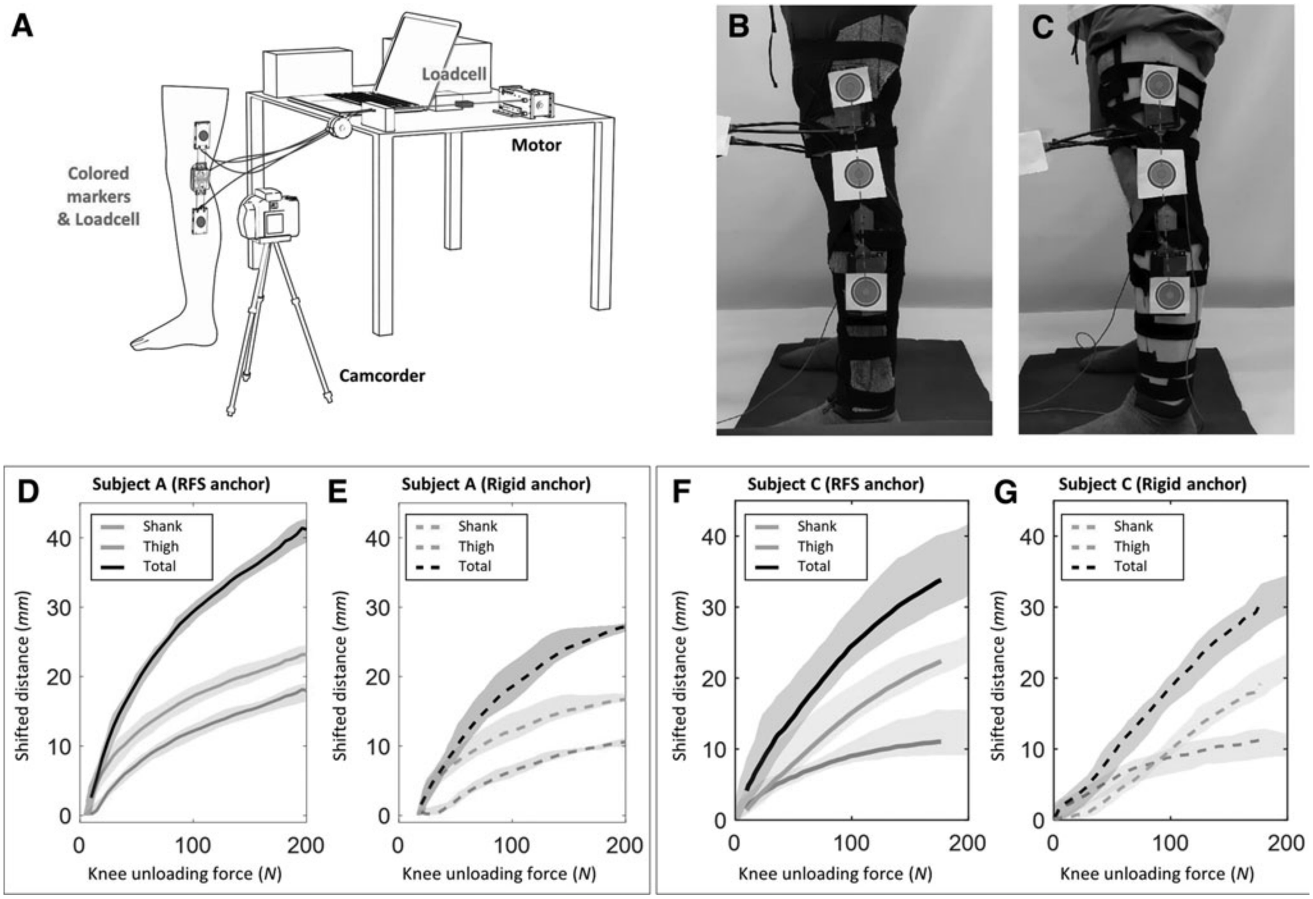

FIG. 8. An experiment evaluating the unloading capabilities of Exo-Unloader. **(A)** Exo-Unloader's TDLS actuators were actuated using an off-board control system, and the relative position of three markers attached to the thigh, knee joint center, and shank during actuation was recorded using a camcorder and measured using MATLAB's image processing toolbox. Exo-Unloader's RFS anchoring **(B)** was comparatively evaluated against **(C)** a rigid anchor of same design. **(D, E)** Subject A experimental results for both the Exo-Unloader and its custom-made rigid unloader counterpart. **(F, G)** Subject C experimental results for both the Exo-Unloader and its custom-made rigid unloader counterpart. Exo-Unloader shifted ≈10–15 mm more than the rigid unloading system condition for both subjects.

wearable robots by the authors of this work and presented in subsequent publications.

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Supplementary Material

Supplementary Figure S1
Supplementary Figure S2
Supplementary Figure S3
Supplementary Figure S4
Supplementary Table S1
Supplementary Movie S1

References

1. Yan T, Cempini M, Oddo CM, et al. Review of assistive strategies in powered lower-limb orthoses and exoskeletons. Robot Auton Syst 2015;64:120–136.
2. Young AJ, Ferris DP. State of the art and future directions for lower limb robotic exoskeletons. IEEE Trans Neural Syst Rehabil Eng 2017;25(2):171–182.
3. In H, Kang BB, Sin MK, et al. Exo-Glove: A wearable robot for the hand with a soft tendon routing system. IEEE Robot Autom Mag 2015;22(1):97–105.

4. Wehner M, Quinlivan B, Aubin PM, et al. A lightweight soft exosuit for gait assistance. In: Proceedings of IEEE International Conference on Robotics and Automation. IEEE: Karlsruhe, Germany; 2013; pp. 3362–3369.
5. Asbeck AT, De Rossi SMM, Galiana I, et al. Stronger, smarter, softer: Next-generation wearable robots. RAM 2014;21(4):22–33.
6. Ding Y, Galiana I, Asbeck AT, et al. Biomechanical and physiological evaluation of multi-joint assistance with soft exosuits. IEEE Trans Neural Syst Rehabil Eng 2017;25(2): 119–130.
7. Asbeck AT, Dyer RJ, Larusson AF, et al. Biologically-inspired soft exosuit. IEEE 13th International Conference on Rehabilitation Robotics (ICORR), Seattle, WA, USA; 2013; pp. 1–8; doi: 10.1109/ICORR.2013.6650455
8. Yandell MB, Tacca JR, Zelik KE. Design of a low profile, unpowered ankle exoskeleton that fits under clothes: Overcoming practical barriers to widespread societal adoption. IEEE Trans Neural Syst Rehabil Eng 2019; 27(4):712–723.
9. Choi H, Kang BB, Jung BK, et al. Exo-Wrist: A soft tendon-driven wrist-wearable robot with active anchor for dart-throwing motion in hemiplegic patients. IEEE Robot Autom Lett 2019;4(4):4499–4506.
10. Jung Y, Phan CB, Koo S. Intra-articular knee contact force estimation during walking using force-reaction elements and subject-specific joint model. J Biomech Eng 2016; 138(2):1–9.
11. Willson J, Torry MR, Decker MJ, et al. Effects of walking poles on lower extremity gait mechanics. Med Sci Sports Exerc 2001;33(1):142–147.
12. Thoumie P, Marty M, Avouac B, et al. Effect of unloading brace treatment on pain and function in patients with symptomatic knee osteoarthritis: The ROTOR randomized clinical trial. Sci Rep 2018;8(1):1–9.
13. Brooks KS. Osteoarthritic knee braces on the market: A literature review. J Prosthetics Orthot 2014;26(1):2–30.
14. Budarick AR, MacKeil BE, Fitzgerald S, et al. Design evaluation of a novel multicompartment unloader knee brace. J Biomech Eng 2020;142(1):1–8.
15. Disc Disease Solution, Inc., Kneetrac Lite: Decompression Knee Brace. Available from: https://discdiseasesolutions.com/products/kneetrac-lite [Last accessed: June 01, 2021].
16. Kutzner I, Küther S, Heinlein B, et al. The effect of valgus braces on medial compartment load of the knee joint—In vivo load measurements in three subjects. J Biomech 2011;44(7):1354–1360.
17. Pollo FE, Otis JC, Backus SI, et al. Reduction of medial compartment loads with valgus bracing of the osteoarthritic knee. Am J Sports Med 2002;30(3):414–421.
18. Kwon J, Park JH, Ku S, et al. A soft wearable robotic ankle-foot-orthosis for post-stroke patients. IEEE Robot Autom Lett 2019;4(3):2547–2552.
19. Jarrassé N, Morel G. Connecting a human limb to an exoskeleton. IEEE Trans Robot 2012;28(3):697–709.
20. Wang D, Lee KM, Guo J, et al. Adaptive knee joint exoskeleton based on biological geometries. IEEE/ASME Trans Mechatronics 2014;19(4):1268–1278.
21. Zanotto D, Akiyama Y, Stegall P, et al. Knee joint misalignment in exoskeletons for the lower extremities: Effects on user's gait. IEEE Trans Robot 2015;31(4):978–987.

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