Kinethreads: Soft Full-Body Haptic Exosuit using Low-Cost Motor-Pulley Mechanisms

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Figure 1: Kinethreads is a practical, low-cost, string-driven exosuit for VR. Our system is able to render a wide variety of immersive kinesthetic forces (red arrows) and vibratory effects (orange zigzags). In these example scenes, haptic effects include object weight (A), impacts from projectiles (B), force from linear acceleration (C), centripetal force (D), object vibration (E), and force feedback (F). The insets on the right show our pulley (green circle) and motor reel (yellow circle) mechanisms.

Abstract

Our bodies experience a wide variety of kinesthetic forces as we go about our daily lives, including the weight of held objects, contact with surfaces, gravitational loads, and acceleration and centripetal forces while driving, to name just a few. These forces are crucial to realism, yet simply cannot be rendered with today's consumer haptic suits, which primarily rely on arrays of vibration actuators built into vests. Rigid exoskeletons have more kinesthetic capability to apply forces directly to users' joints, but are generally cumbersome to wear and cost many thousands of dollars. In this work, we present Kinethreads: a new full-body haptic exosuit design built around string-based motor-pulley mechanisms, which keeps our suit lightweight (<5kg), soft and flexible, quick-to-wear (<30 seconds), comparatively low-cost (~$400), and yet capable of rendering expressive, distributed, and forceful (up to 120N) effects. We detail our system design, implementation, and results from a multi-part performance evaluation and user study.

CCS Concepts

• **Human-centered computing** → **Haptic devices**.

Keywords

Haptics, Force Feedback, Exosuit, Virtual Reality, Wearables

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1 Introduction

Haptic perception is generally organized into two main pillars: tactile sensations (texture, friction, pressure, etc.) and kinesthetic sensations (force feedback, weight, muscle effort, etc.). Contemporary consumer XR haptic devices — from controllers to suits — are almost exclusively vibratory, and can render (or approximate through sensory substitution) many high-value tactile sensations. However, these devices are incapable of rendering kinesthetic forces, leaving haptic experiences incomplete.

In this work, we describe a new haptic suit capable of rendering both vibrotactile *and* kinesthetic effects. Our core hardware design uses a small array of computer-controlled, motorized reels coupled with a variety of string-based mechanisms, such as pulleys and capstans. These mechanisms can be used for different purposes: for example, to create a mechanical advantage that can better match human strength (without increasing motor size), or to reroute or distribute forces over larger areas of the body. This combined approach allows us to achieve numerous key design goals, including:

- Soft, flexible, and safe design
- Comparatively low-cost (~$400)
- Lightweight (<5kg)
- Quick and easy to wear (<30 seconds)
- Multi-hour runtime on battery power
- Full-body, independent limb, haptic actuation
- High-bandwidth vibrotactile effects (up to 200Hz)
- Strong kinesthetic effects (up to 120N)

As we will discuss more in related work, rigid exoskeletons can achieve a similar range of effects, but are generally heavy, cumbersome to wear, and cost many thousands of dollars. More similar to our work are soft kinesthetic exosuits, of which a handful exist (see Figure 3). However, none have full-body coverage, nor were any designed or evaluated for haptic rendering or XR use cases, instead targeting rehabilitation, accessibility, and strength augmentation. In contrast, we exclusively focus on haptics and XR with a consumer-oriented mindset, giving this work a different design ethos, objective function, evaluation scope, and success metric.

After detailing our design and implementation of Kinethreads, we enumerate a non-exhaustive list of expressive kinesthetic forces one might encounter in XR experiences (e.g., centripetal force, high gravity, object weight, body compression, explosions). We combine our system's expressive capabilities into a suite of demo scenes, which we use to convey the feasibility of our system, and which we evaluate in a user study. The latter dovetails with a performance evaluation to quantify our system.

2 Related Work

Kinethreads is a string-based, full-body exosuit for haptics, which intersects with three key bodies of work: exosuits (and exoskeletons) for haptics, string-based exosuits (none of which are intended for haptics specifically), and string-based haptic systems (none of which are full-body exosuits).

2.1 Active Exoskeletons & Exosuits for Haptics

Wearable exoskeletons were first introduced in the 1960s as a form of human augmentation [43]. To narrow our focus in this broad field, we only review exoskeletons and exosuits that are intended to be used for haptics, as many systems exist for other purposes such as muscle rehabilitation or strength augmentation [12, 46, 47, 57]. However, we do cover non-haptic active exosuits that utilize a similar actuation method to ours (i.e. motors + string/cable) in the section below. We also do not consider passive exoskeletons [7, 26, 68] as they cannot be used for computer-controlled rendering of haptic effects.

Within haptic suits, rigid exoskeletons are the least similar to ours. Due to the cost and difficulty of use of these devices, very few are designed for the sole purpose of haptics, and instead take advantage of powerful motors to provide muscle augmentation or medical assistance. However, systems like Bionic Yantra [72] have explored gamifying rehabilitation through interactive haptics in VR. Exit Suit [60] is a hybrid rigid-soft exoskeleton that is specifically for VR, but is mounted on a fixed platform and therefore immobile.

More consumer-friendly and related to our present work are "soft" exosuits that minimally constrict user movement. Of the examples that were designed for haptics, none use strings. The most adopted technology for haptic wearables is vibrotactile actuators, though few come in full-body form factors; we only consider a wearable a "suit" if it covers more than one body region. Many vibrotactile suits exist both in research [20, 29] and commercially [11, 61, 71]. However, these cannot be used for force haptics.

Most related to our work are soft exosuits that render forces to the user. For example, prior research has looked into pneumatic exosuits that use actuated airbags [13, 22, 28] or gel muscles [30] to direct force around the body. HASEL actuators can also be used to create artificial muscle suits [73], using electrostatic forces rather than pneumatics to create hydraulic pressure. Kinesthetic haptics can also be achieved through interfaces that "freeze" and squeeze the body, using shape memory alloys [16] or jamming [4]. Finally, prior work has also looked at utilizing electrical muscle stimulation to simulate force feedback by directly contracting the muscles themselves [36–38], though these systems are more patches than suits. The TESLASuit does integrate EMS directly into a suit that retails for $13,000 [64]. For a direct comparison of these broad categories of kinesthetic haptic suits to our own, please see Figure 2.

2.2 String-Based Exosuits (not for Haptics)

Many soft exosuits are not explicitly made for haptics, but still impart kinesthetic forces to a wearer. Some suits do this passively (i.e., no motors or batteries) through elastic bands [24], which is less similar to ours. Instead, we focus on exosuits using active string- or cable-based mechanisms. Most of the systems under development or available for commercial retail are meant to support or augment body functions, such as mobility assistance [45, 51], gait training [8], rehabilitation [62], core body support [52], and strength augmentation [5, 6, 32]. A summary and comparison of these can be seen in Figure 3. These systems have motors that pull on or reel in cables or wires that impart forces to a user. However, because most of these are designed for rehabilitation or strength-augmentation purposes, rather than for haptics, the forces that they impart are typically more directed and greater than we need. As a result, such systems tend to use much larger and more expensive motors and only focus on one or two body regions, while weighing as much or more than Kinethreads, and costing significantly more. Additionally, most of these systems have never been utilized or tested in VR; only CRUX [32, 33] briefly discusses the possibility of haptics in VR as a potential use case. CRUX uses six hobby-grade DC motors attached to string reels, routed to one arm. To achieve sufficient torque, CRUX motors use 1000:1 gearboxes, which would introduce substantive latency, impeding real-time force feedback effects. The authors never specify or evaluate system latency or achieved force, precluding further comparison.

	Stationary Rigid Exoskeleton	Mobile Rigid Exoskeleton	Vibrotactile Vest/Suit	Artificial Muscle Suit	Mechanical Joint Jamming Suit	Electrical Stimulation Suit	Pneumatic Jacket	String Exosuit
Example System	EXIT Suit [60]	Bionic Yantra [72]	bHaptics TactSuit [11]	Meta Suit [73]	Frozen Suit [4]	TESLASuit [64]	Force Jacket [13]	**Kinethreads (Ours)**
Form Factor	Mounted Frame & Attached Suit	Moving Frame & Exoskeleton	Vest + Limb Accessories	Sleeves on Body	Patches on Body	Full-Body Exosuit	Jacket	Vest + Limb Straps
Haptic Capability	Kinesthetic, Vibrotactile	Kinesthetic	Vibrotactile	Kinesthetic	Kinesthetic	Kinesthetic, Vibrotactile	Kinesthetic	Kinesthetic, Vibrotactile
Body Regions	Full Body	Torso, Legs	Torso, Ankles, Wrists, Face	Arms, Legs	Arm & Leg Joints	Torso, Arms, Legs	Torso, Arms	Torso, Hands, Feet, Face
Actuation Method	Motors	Motors	Vibration Motors	Hydraulic Electrostatic	Pneumatic Jamming	Electrical Muscle Stimulation	Pneumatic	Motor Reels
Cost	~$10,000+	~$50,000+	$1,100	~$500	~$200	$13,000	~$200	$420
Weight	~100kg	~200kg	3kg	~5kg	~5kg	~5kg	~5kg	4.6kg
Wear Time	~15 min	~20 min	~<1 min	~<3 min	~<3 min	~<5 min	~<1 min	<1 min

Figure 2: Table of related work comparing other haptic exosuit and exoskeleton technologies to ours. Tildes mean the value was not reported and is thus estimated.

	Intended Use	Arms	Head	Back	Front	Legs	Cost	Weight	Max F
Myosuit [51]	Mobility Assistance	No	No	No	No	Yes	~$10k+	4.6kg	435N
XoSoft [45]	Mobility Assistance	No	No	No	No	Yes	~$3k+	~3.0kg	~50N
EasyWalk [62]	Rehabilitation	No	No	No	No	Yes	~$5k+	3.0kg	~150N
Seismic [52]	Core Body Support	No	No	Yes	Yes	Yes	~$3k+	2.5kg	~50N
Asbeck et al. [6]	Strength Augmentation	No	No	No	No	Yes	~$10k+	10.1kg	200N
ReStore Exo-Suit [8]	Gait Training	No	No	No	No	One	$29k	5.0kg	~50N
CRUX [32]	Strength Augmentation	Yes	No	No	No	No	~$300	~2.5kg	~10N
Kinethreads (Ours)	Haptics in VR	Yes	Yes	Yes	Yes	Yes	$420	4.6kg	120N

Figure 3: Closely related string-driven exosuits. Tildes mean the value was not reported and is thus estimated. Listed is total weight, including system, suit, and batteries.

2.3 String-Based Haptics

Though the string-based exosuits in prior work are not primarily intended for haptics, several string-based haptic systems exist outside of a suit format. For example, haptic tangibles can be string-actuated, and they can be designed to be held by users like VR controllers [56, 70] and custom tangible objects [48], or they can be directly attached to the user [1, 2, 42]. There are also large string-actuated systems that are installed in the environment, and can actuate the user's entire body [41].

Many string-based haptic systems focus specifically on the hand, since this allows the fingers to be actuated without having to directly attach motors to the joints, which can be cumbersome and fatiguing over time. Rather than pulling on the fingers directly, systems have experimented with using brakes on cables or elastic bands to prevent motion rather than apply active force [17, 65] or passively apply feedback [3, 69]. These systems lack dynamic string or elastic length control, rendering them unable to do precision haptics. Active string-based gloves have used methods such as twisted string actuation [15, 25, 31, 59], which is a method where motors twist one or more strings together, causing the string length to contract and impart a pulling force. Other systems use Bowden cables, which allow both push and pull forces to be transferred a small distance, as long as the cable is properly tensioned [19, 44] (more discussion on this mechanism in Section 3.6.7).

Most similar to Kinethreads are haptic systems that have motors actively pulling and reeling in strings. Many of these are attached to the fingertips, and can be externally mounted [35, 50], or the motors are housed elsewhere on the body, like the back of the hand or forearm [9, 40, 63], or the head or shoulder [14, 55]. These latter systems utilize a similar principle to our system, in that they anchor the motors at a load-bearing location where the equal and opposite force will be somewhat masked (i.e., the shoulder [14]). As a full-body system, Kinethreads anchors the motors around the waist, where they are the least obtrusive.

In summary, while prior work explores soft exosuits for assistive purposes and string-based haptics for partial-body systems, Kinethreads uniquely combines full-body string-based actuation with kinesthetic and vibrotactile rendering, optimized for XR immersion, affordability, and wearability.

3 Implementation

Our Kinethreads suit combines custom hardware, firmware, and software to create a full-body, low-cost, soft haptic exosuit utilizing motor-pulley mechanisms for kinesthetic and vibrotactile effects, seen in Figures 1 and 4. To encourage replication, we open-source our system at https://github.com/FIGLAB/kinethreads.

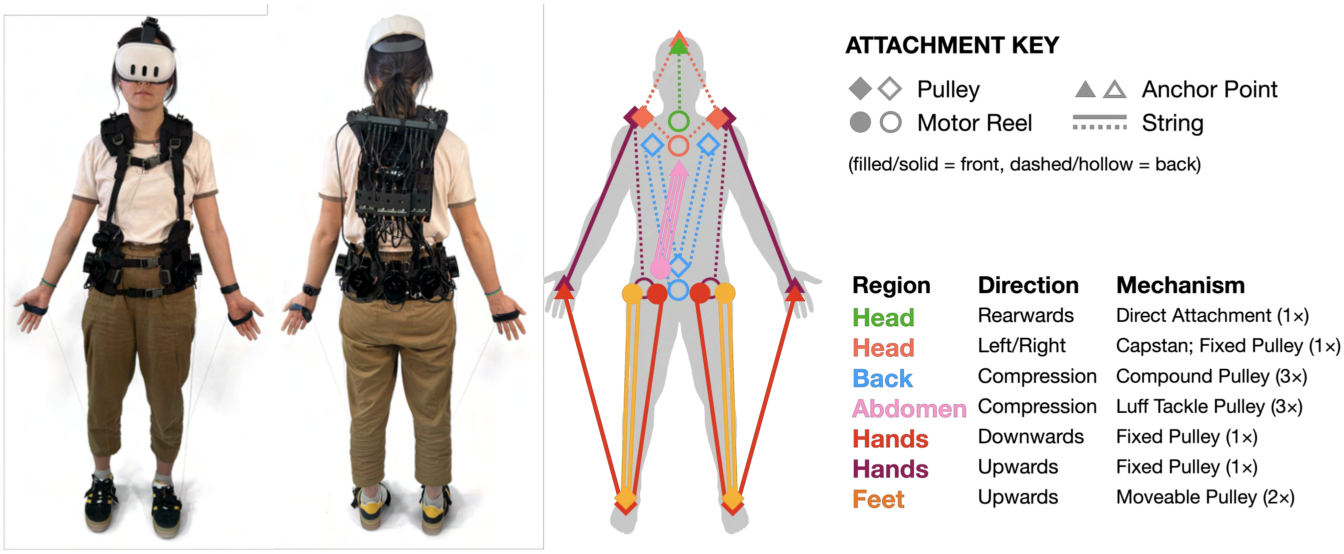


Figure 4: An overview of the motor reel placements and mechanisms on our exosuits. To the left are two photos of a user wearing Kinethreads. In the middle is a schematic with the placement of our motors, pulleys, anchor points, and the connecting strings, color-coded according to body region. On the right is an attachment key, as well as a table detailing corresponding force directions, pulley mechanisms, and mechanical advantage multipliers.

3.1 Suit

We investigated many commercial off-the-shelf vests and harnesses to serve as a base for our system. In general, we found that harnesses for climbing and construction were needlessly heavy-duty (designed for high dynamic loads in the case of falls) and too cumbersome to wear/remove (especially with thigh/groin straps) for consumer-oriented uses. Most suitable among the designs we considered were tactical vests, which have several useful features that make them ideal for our prototype. First, they are designed for long periods of wear and so are optimized for comfort, effectively distributing load among the back, shoulders, and waist. Second, they can be put on quickly using commonplace plastic side-release buckles as opposed to pass-through metal ones, and have many different adjustable straps. Third, these vests offered many useful mounting points — the final design we chose was a common Modular Lightweight Load-carrying Equipment (MOLLE) vest. As the name implies, this specification offers a distributed array of standardized attachment points across the body, known as the Pouch Attachment Ladder System (PALS) webbing. Not only are the individual attachment points load-rated, but the entire vest is designed to secure loads to the body. Our motor reels and string mechanisms are affixed to the vest using a mix of MOLLE-compatible acrylic plates and 3D-printed clips.

In addition to our vest, we attach strings to the hands using velcro loops that wrap around the palm. For the legs, strings terminate in adjustable looped straps with plastic buckles that can be quickly clipped around feet or shoes.

3.2 Motor Reels & Placement

Our suit contains ten motorized reels able to render haptic effects to seven distinct areas of a user's body: 2× hands (with two force vectors each), 2× legs, abdomen, back, and head (with three force vectors). Motor placements can be seen in Figure 4. Eight of our motors are placed around the user's waist for two important reasons. First, this is an ergonomic location to bear (and hide) the weight of the motors [21]. Second, any pulling forces generated by the motors have an opposite pull on the vest where the motor is affixed, which is generally an unintentional force that is not aligned with the haptic scene. However, by placing the motors at the waist, further coupled to the torso with a well-designed and secured vest, the forces imparted by the motors are obfuscated by virtue of a significant mismatch in body mass between the torso and most end points (Wireality [17] and ReelFeel [14] leveraged the same idea). Put simply, a string connection between a mobile limb (hand, leg, head) and torso, with equal but opposite forces applied at both ends, will be felt much more significantly at the limb. Third, our motors are mounted flush to the vest, such that strings exit in-plane with the vest and torso. This means that the force felt by the user is lateral, which we found to be more subtle than a normal force vector (i.e., pulling away from the body).

An exploded view of our motor reel design can be seen in Figure 5. Each motor is mounted to a MOLLE-compatible laser-cut acrylic plate with screws, which pairs with a sister plate to enable fixation onto our vest. This mount also integrates an AS5048A magnetic rotary encoder under the motor, and a string guide next to it. On the spinning side of the motor, we mount a single thin piece of laser-cut acrylic as a reel hub with an inner diameter of 30mm. Stacked together, the total thickness of our motor reel is 3.0cm.

In order to impart large forces with relatively small motors, we selected high-torque brushless DC (BLDC) gimbal motors. This class of motor has stators wound with many more turns than other motors of the same size, giving them a higher reactance and the

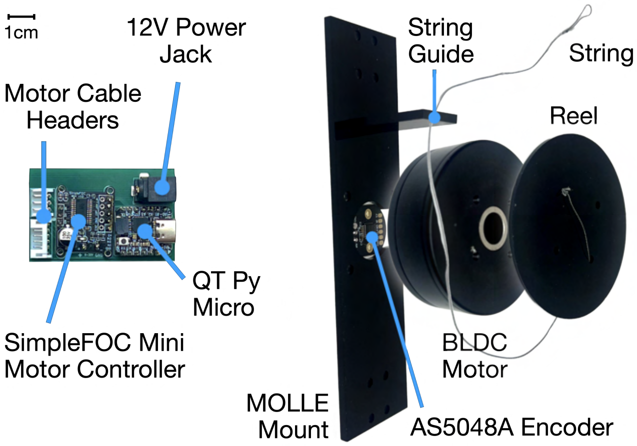


Figure 5: Left: Motor control PCB. Right: An exploded view of one motor reel.

ability to deliver high torque continuously throughout their entire rotation. BLDCs have very low cogging torque, enabling smooth and continuous motion (not possible, e.g., with traditional stepper motors). This optimized trade-off of high torque and small size make these motors ideal for our application.

For modularity, we selected two models of motor (p.n. MYH-6823F and MYH-4625F). Future work could save on weight and cost by carefully pairing motor size with force requirements, which varies across the body (e.g., head effects generally need much less force than legs). The larger motors we selected are 23mm thick, 68mm in diameter, and weigh 265g each. When integrated into our reel design, the string has a maximum direct pulling force of 42N at 15.6W. Our smaller motors are 25mm thick, 46mm in diameter, and weigh 140g each. When integrated into our smaller reel design, the string has a maximum direct pulling force of 17N at 14.4W.

3.3 Drive Electronics & Firmware

Each motor is connected to a custom driver PCB (Figure 5, left), which acts as a motherboard for a QT Py microcontroller [27] and a SimpleFOCMini v1.0 motor driver [58]. All ten QT Py boards are connected to a USB hub (seen in Figure 6), and USB C connections provide power and serial communication to/from a host computer. Our PCB design places many drivers side-by-side, which can be cut to length, with motors powered by a common 12V rail. For motor power, we use either a wall-powered DC power supply or a 12V LiPo battery pack (we discuss power consumption in Section 4.3).

To enable closed-loop control, the aforementioned AS5048A encoder provides absolute motor rotation (read by the QT Py over SPI). Without a torque/force sensor, our control stack cannot detect force output or input by the user; instead, we continuously track motor position and speed for state information. For motor control, we use the open-source SimpleFOC library [58] to command the motors to a desired power, directly proportional to torque and string pull force. The main control loop operates at approximately 2kHz on our QT Py microcontroller. Our firmware receives motor commands over USB serial from our Unity-based software (Section 3.9).

Figure 6: The main components of our vest.

3.4 String Slack & Auto Reeling

If there is slack in a string, there will be a brief delay in imparting force on the body part until the slack is taken up. For longer-duration forces (>200ms) — such as object weight, gravity, and linear acceleration — this is not a significant issue; it simply adds some latency before the force is rendered to the user's body. It is, however, more problematic for short-duration force effects (<200ms) — like collisions and explosions — because the slack might not be taken up in such a small actuation period. (We note that the latency from taking in the string slack is different from force latency when there is no slack, which we quantify in Section 4 and Figure 9.)

We minimize this slack in two ways. First, every time the system loads into a new VR scene, the motors are commanded to reel in all slack as part of an initialization procedure. The firmware monitors motor rotation angle, and once the motor stops reeling (i.e. the motor angle does not change even though torque is still being applied), we can assume it is meeting resistance from the user. This means that all slack has been taken up, so the motor immediately disengages. Second, during VR experiences, if we detect no motor rotation, we lightly tug on the string to test for resistance. If we detect none, we reel in slack with very low torque. As before, we stop reeling when either the reel stops (i.e., slack removed) or begins to reel out (i.e., from user movement). Although user movement backdrives the motors, BLDC motors are built to handle back EMF.

3.5 String Routing Considerations

An important design goal was to minimize the number of strings running through the air, as this is obviously less elegant and potentially more damage-prone. Ideally, all strings would be contained

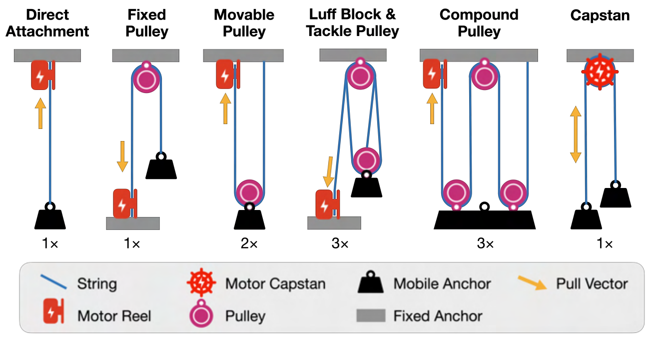


Figure 7: A schematic illustration of the six string mechanisms we use to route, distribute, and amplify the forces from our motor reels and capstans. Mechanical advantages are written below each configuration.

within the suit itself, but this is not possible for the legs and arms without full-body sleeves and pants. While we strongly considered the latter, we ultimately decided against such a design, as it made the suit significantly more cumbersome to wear, harder to fit a variety of body types, and was aesthetically intrusive. We note, however, that the general idea of using low-cost motor-pulley mechanisms can certainly be applied to a full-body suit design with sleeves and pants; it was just not the design we chose to prototype.

String routings that leave the vest and run through the air (legs, arms, head) were designed such that the accidental tangling of strings is virtually impossible. We also take advantage of string mechanisms (described next) that provide force magnification while running strings along the same vector, minimizing volume and unnecessary crossing points. Another design choice was to have two different strings connect to each hand's palm strap, giving us two force vectors with which to actuate each hand, enabling a greater array of force effects for hand interaction.

3.6 String Mechanisms

Humans have been making and using rope and strings for tens of thousands of years [23, 67], and as such, have deeply explored and developed many string-based mechanisms. In this work, we take advantage of several of these fundamental mechanisms, including pulleys and capstans. Crucially, these mechanisms not only allow us to 1) *amplify force*, but allow us to usefully 2) *redirect force* and 3) *distribute force*, enabling more compact implementations while also expanding our expressive capabilities. Figure 4 provides a schematic overview of the mechanisms we employ in our suit. We use braided nylon string for all of the mechanisms.

3.6.1 Direct Reel Attachment. Starting most basic, we can simply attach the string exiting a motor reel to a point on the body (Figure 7, first). This is the mechanism that has been most commonly utilized in prior work [9, 14, 35, 40, 50, 55, 63]. This configuration provides no mechanical advantage and is best suited for rendering modest forces or in areas with limited space for integration. In our suit, we only used direct attachment to pull the head backwards.

3.6.2 Fixed Pulley. A fixed pulley uses a single pulley affixed to a non-moving point (Figure 7, second); the string exiting the motor reel is routed through the pulley and attached to an end point. This arrangement provides no mechanical advantage, but allows for force rerouting. Prior systems that route the strings around the body inherently have fixed pulleys around the joints, even if they did not describe it as such [5, 6, 32]. We use this design for both of our hand attachments (Figure 4). Specifically, we use motors mounted to the back of the vest, with strings that route over the shoulders, through a frictionless plastic cable housing, and then down to each hand to provide an upwards force on each hand. We also use motors mounted to the front of the vest, which are routed down through a frictionless metal ring on the foot strap, and then back up to the bottom of the hand, providing a downwards force for each hand.

3.6.3 Movable Pulley. A movable pulley (Figure 7, third) is very similar to a fixed pulley design, but the pulley attachment point is mobile and generally where one wishes to apply force. Although the terminal, fixed end can be located anywhere on the body, we always anchored it near the originating motor reel for compactness (in this way, both outbound and inbound strings travel along the same vector). This arrangement provides a 2× mechanical advantage, which we use for our legs, as they require greater forces than other parts of the body, owing to their mass and muscle strength.

3.6.4 Block and Tackle Pulley. A block and tackle pulley (Figure 7, fourth) allows strings to be looped multiple times through the two pulleys (called "reeving") to linearly increase mechanical advantage [67] with very little increase in physical volume, as the strings pass back and forth along the same vector. In this way, block and tackle arrangements can be easily scaled up with more passes, many of which have special names: gun tackle=2× mechanical advantage, luff tackle=3×, double tackle=4×, gyn tackle=5×, threefold purchase=6×, etc. We use a luff tackle arrangement for actuating the abdomen, allowing us to impart large forces using our smaller motor model, chosen to minimize weight on the front of the torso.

3.6.5 Compound Pulley. Like block and tackle pulleys, compound pulleys can provide greater than 2× mechanical advantage. Instead of looping string through a pair of pulleys many times, a compound pulley simply uses many passes through many pulleys (Figure 7, fifth). Every pulley in the system shares the force equally, which means this design has the unique ability to distribute force over many more points (i.e., larger area) than any of the previous designs, while also increasing mechanical advantage. We use this property to great effect on the back of the user, which has a large surface area (compared with the hands or head) that also generally requires high forces owing to its muscular nature. Specifically, we use 3 pulleys to distribute the force and generate 3× mechanical advantage (up to approximately 120N of force).

3.6.6 Capstan. Most of our motor reels have a single port from which string enters or leaves, and the internal spool either accumulates or releases string. Capstans are very related mechanisms [67], but have two string ports — instead of a spool that accumulates string, the string is looped around an internal spool and then exits (Figure 7, last). When the motorized capstan turns in one direction, it draws in string from one port and releases string out the other, and vice versa when turning in the opposite direction. This means we get two equal and opposite actuation capabilities from one motor. As an example, we use a capstan to actuate forces on the left and right of the user's head, since our demos never actuate both head directions at once; this reduces the cost and weight of the suit by using one motor instead of two. Like reels, capstans can be combined with pulleys to achieve different effects and capabilities.

3.6.7 Other Mechanisms & Bowden Cables. We note that there are other string mechanisms we did not adapt, but which almost certainly have interesting uses in soft haptic exosuits, including differential pulleys, windlasses, and rope drives. We also considered using Bowden cables (used in many robotics and haptic systems [19, 25, 34, 44]) for some areas of our suit as an alternative to string. Bowden cables can usefully provide both pull and push forces, whereas strings can only pull. The typical arrangement of Bowden cables is to route forces to a specific body joint, and apply push/pull forces in line with that joint's degrees of freedom. Most often, the actuation stroke length is just few centimeters (similar to hydraulic actuation, just using a steel cable housed in a semi-rigid sheath instead). This works well for body areas with limited travel, such as the fingers or wrist, but does not work with limbs such as the arms and legs. We found our string mechanisms had to operate over ranges as close as 10cm to approaching 1m. Further, strings are a natural complement to pulley systems (whereas Bowden cables offer no mechanical advantage), and we make full use of this ability to create a compact, yet high-force suit.

3.6.8 Mechanical Advantage vs. Actuation Latency. As discussed, many pulley designs provide force multiplication — in our suit, this ranges from 1× to 3× mechanical advantage, allowing us to use smaller/lighter motors. However, this added force does not come entirely for free. To achieve e.g., 2× mechanical advantage requires 2× the length of string to be ingested by the reel. The extra length takes more time to reel in, and thus increases the latency of haptic effects (roughly linear with mechanical advantage; see Performance Evaluation in Section 4 and Figure 9).

3.7 Feet Tracking

The Quest 3 we use does not offer native feet tracking. However, some haptic scenes may require basic tracking of the feet to greatly enhance the expressive functionality. For example, we explored a demo scene where users could step on wooden crates to break them, creating a momentary impulse effect. In another scene, users walked through a branch-covered forest floor and felt crunching sensations with each step, just before their foot made contact with the ground. In both cases, the height of each foot was used as a haptic event trigger. To achieve these haptic experiences, we built a rudimentary foot tracker using the absolute motor rotation reported by the motor encoders, which directly correlates with how much string has been unspooled. In the two example scenes above, we assume the user is standing when the scene is loaded, and we record both leg reel motor rotation values as a zero baseline. We can then approximate the extension of each foot by continuously reeling in the string at low torque and checking how much has been reeled out. Such a solution is unnecessary if future headsets can provide native leg tracking capabilities.

3.8 Vibration Effects

In addition to kinesthetic effects, our motor reels can also be used for vibration haptics, up to a bandwidth of a few hundred Hertz (see experiment in Section 4.2 and Figures 8 and 9). For a simple oscillatory signal, the motors can be commanded to push and pull at a fixed frequency. Of course, more dynamic effects can be rendered by commanding the motors with functions such as Perlin noise or arbitrary waveforms. Our API allows vibration effects to be layered on top of any kinesthetic haptics, adding complexity and immersion.

3.9 VR Software & Haptic Control

Our example VR scenes were all developed in Unity [66]. The authoring process for haptic effects is similar to sound design in VR: 1) We can have continuous background haptic effects (akin to environmental sounds or background music); 2) we can have haptic effects triggered by events (e.g., object collisions, weapons fire); and 3) we can have haptic effects parametrized by in-VR values and states (in much the same way, e.g., a engine sound can be varied by virtual engine RPM in a racing game).

Our API allows us to stack any number of haptic effects, which is a simple superimposition of the signals. For example, if we command a reel to render a 50Hz 5N vibration effect and a 20N static (kinesthetic) force, the resulting force signal will be 50Hz sinusoid oscillating between 20N and 25N. This capability is useful when designing VR scenes, when there can be multiple contributing haptic sources. For instance, in our runaway train scene (Figure 19), we independently authored a high-frequency vibration effect and a train car swaying kinesthetic effect (linked to the train's rotation, which was controlled by a Perlin noise function). Similarly, in our car demo (Figure 14), we independently author effects for engine vibration, force from linear acceleration, and centripetal forces.

When our suit is tethered to a computer, our Unity application sends commands to our motor driver electronics over USB serial. In our untethered version, Unity sends commands over websockets to a RaspberryPi Zero 2W, which then relays those commands to our motor driver board over USB serial.

3.10 Cost

Keeping cost low was an important design goal. At a high level, we strove for exoskeleton-quality effects with vibrotactile vest prices. In this regard, we believe our system achieves a novel and interesting Pareto-efficient middle ground.

In total, our one-off suit cost us around $650 to construct at single-unit retail prices. In commercial quantities (10K units, numbers obtained by email quotes requested from manufacturers and wholesalers), we estimate the cost would be around $420. Using the latter volume pricing, the most expensive component in our system is the motors: $35 and $20 for our seven large and three small motors, respectively, for a total cost of $305. When untethered, our suit is powered by a $20 12V 5600 mAh Li-ion battery designed for high discharge rates (63W). Moving to smaller parts: microcontrollers cost $4.50 each, motor drivers cost $2.00 each, rotary encoders cost $1 each, and MOLLE vests cost $16. Various 3D prints and plastic pieces totaled less than $3. Please see our repository for the full bill of materials (https://github.com/FIGLAB/kinethreads.).

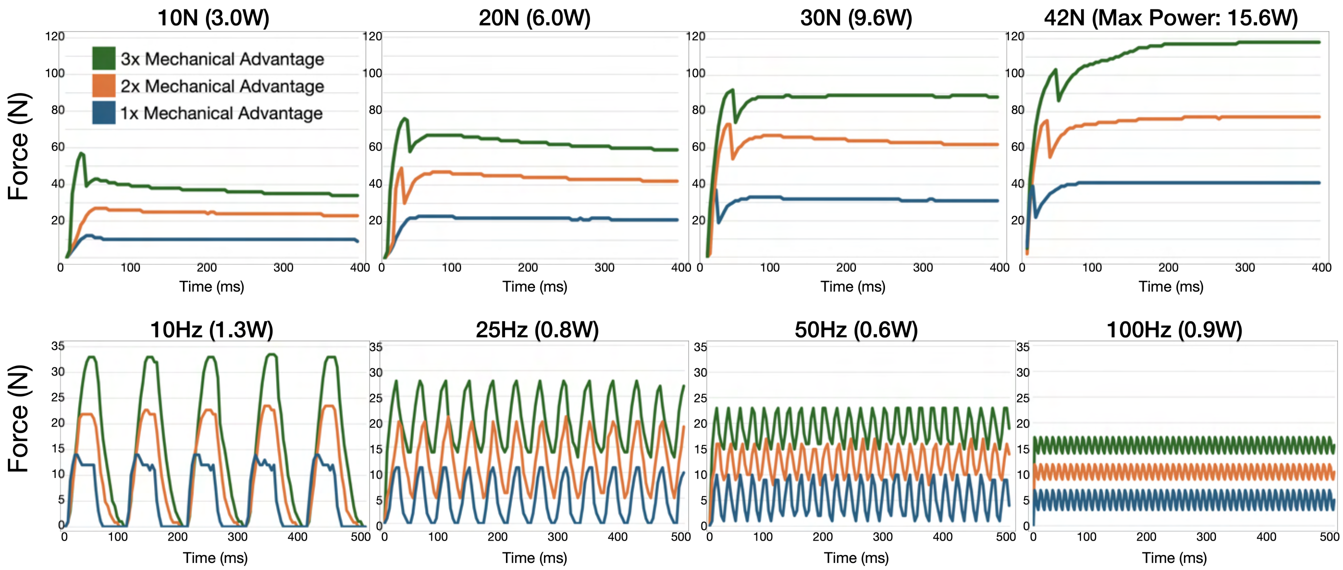


Figure 8: Plots over time for four static forces and four vibratory signals. In each condition, we captured data for three pulley systems (direct attachment, movable pulley, and luff block and tackle) representing 1×, 2×, and 3× mechanical advantage systems. Power consumption is listed in each heading (in parentheses).

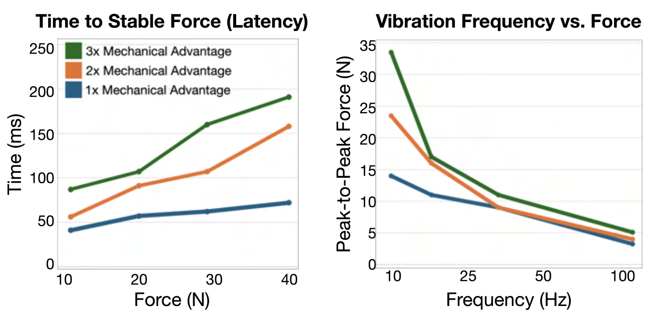


Figure 9: Using data from our static and vibratory force tests (Figure 8), we plot two useful relationships. Left: Time until the motor reel achieves a stable force (i.e., force latency). Right: Peak-to-peak force when rendering vibratory effects.

3.11 Weight & Fit

Our vest weighs 4.6kg (10.1lbs) altogether, including the battery for untethered operation; 2.3kg of weight is from the motors alone. Our MOLLE vest adds another 0.8kg, but it is well worth this weight penalty due to its high-quality design. These vests are specifically designed to carry "common operational loads" of ~9-18kg, and 25kg+ for combat setups. With these significant loads in mind, these vests are designed to keep weight close to the body's center of mass, use multiple adjustable shoulder and waist straps to ensure a snug and distributed fit, and have broad shoulder straps to further distribute weight. We note that no participants expressed discomfort during our user study, and in fact three participants remarked that it felt much more comfortable than it appeared.

4 Performance Evaluation

We conducted a technical evaluation to quantify the main performance parameters of our system. As already noted, the maximum sustained force our large motor reels can generate is ~42N (drawing 1.3A at 12V). In this section, we answer four other fundamental performance questions:

(1) Force: What are the resulting forces when our motor reels are coupled with our various pulley mechanisms?
(2) Latency: How long does it take for the motors to reach their target force, especially when coupled to our various pulley mechanisms, which require additional string to be spooled?
(3) Vibration Force: What are the forces achieved at various vibratory frequencies with our motor-pulley arrangements?
(4) Power Consumption: How much power does the system draw, under typical and max loads?

4.1 Force vs. Latency Measurements

To measure force, we used a M5I Mark-10 force gauge [39] logging data at 250Hz over USB. We use a sturdy rig to hold a single motor under the force gauge, with the ability to swap in and out different pulley systems. Starting first with direct attachment from the reel to the gauge head (i.e., 1× mechanical advantage), we commanded our motor to pull at 10, 20, 30, and 42N of force (the latter being our motor's maximum force). We then repeated this procedure for two other representative pulley systems: a movable pulley (providing 2× mechanical advantage), and a luff tackle (providing 3× mechanical advantage). These results can be seen in Figure 8. For these tests, we also recorded motor power consumption, which is listed in the individual plot headings.

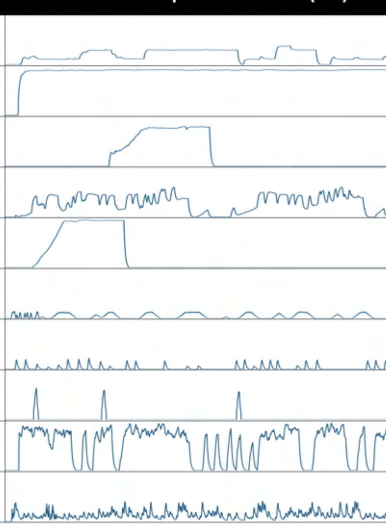
As can be seen in the individual plots in Figure 8 (top row), our motor reels spike in force within the first 50ms, before leveling off at around ~100ms. Our plots follow classic PID responses, where the motor control software attempts to reach the target force as soon as possible by briefly overpowering the motor; once it detects that the motor has achieved the target force, it backs off and settles into a steady state. We plot this latency (time required to achieve a stable force) in Figure 9, left.

4.2 Vibration Force

Using the same force-measuring setup, we recorded output force for different common haptic vibration frequencies: 10, 25, 50, and 100Hz. The motor power is a continuous square wave oscillating between 0W and 4.8W at 12V. To characterize how our string mechanisms interact with vibratory effects, we captured data with the same three string mechanisms as described in the previous section (1×, 2×, and 3× mechanical advantage). The results from these measurements can be seen in Figure 8, bottom row. As one might expect, the higher the vibration frequency, the harder it is for the motor reels to achieve maximum force, especially at higher mechanical advantages, where there is more string to reel in (and not enough time to do so). This relationship is plotted in Figure 9, right. We note, however, that even at 100 Hz, the system can render vibratory forces with peak-to-peak forces above 3N, which remain salient for human perception.

4.3 Power Consumption

Our suit's standby power consumption, with all the electronics running but no active motors, is 1.5W (0.02A at 12V for all ten of the SimpleFOC motor controllers, 0.25A at 5V for all ten of the QT Py microcontrollers). Our suit's theoretical peak power consumption, with all motors on and at maximum torque, is 153.7W (12.7A at 12V for the motors, 0.25A at 5V for the QT Py microcontrollers). We note that in practice, none of our example scenes utilize this max power draw configuration.



Scene	Power Consumption Over Time (60s)	Peak W	Mean W
Held Objects & Backpack		16.6	8.57
Alien Planet		41.0	39.1
Spaceship Launch		35.6	8.7
Car Racing		26.6	12.24
Tied Up by Bandit		44.4	8.7
Wizard Spellcasting		5.7	1.8
Boxing		9.5	1.0
Dynamite Explosion		27.3	0.6
Waterfall		40.9	22.2
Runaway Train		17.6	6.0

Figure 10: Power consumption over a representative 60-second period for the ten example scenes in our user study.

For most of our example scenes, only a subset of motor reels are active (according to the appropriate force vectors needed), and these rarely operate at their maximum force. Moreover, many haptic events are transient, and some are very brief, such as collisions. To provide a useful estimate, we recorded the power draw in all ten of the example scenes used in our user study over a period of 60 seconds using an ACS712-30A current sensor. These demo scenes feature repeated and heavy interaction with the haptic effects, and likely represent an upper-bound of power consumption. Across all demos, we found a mean power draw of 10.9W and a peak power draw of 44.4W. Plots and power consumption numbers for each example scene can be found in Figure 10. Figure 8 also provides power consumption numbers for a set of static and oscillatory forces.

When untethered, Kinethreads relies on a 12V 67.2Wh battery, measuring 3.7×5.7×6.8cm and weighing 288g (with a max output of 63W, below our system's peak draw in practice; see Figure 10). The battery is securely stored in an internal pouch of our vest, and can be recharged using a small 12V barrel jack. Even this modest battery provides more than six hours of runtime if we use our previous mean power consumption of 10.9W. For comparison, the Meta Quest 3 draws ~8.6W of power during use (providing around 2.2 hours of runtime with its 18.9Wh battery). When tethered to wall power, our suit's power draw is negligible (i.e., a typical US residential wall outlet is rated to deliver 1800W of power).

5 Expressive Capabilities & Example Scenes

Our haptic suit can render a variety of useful and interesting kinesthetic and vibratory effects, and we discuss these below through an application- and experience-oriented lens. Many of Kinethreads' expressive capabilities are approximations of real-world forces, which can be surprisingly immersive with coordinated audiovisual stimuli.

We organize our haptic effects into five high-level categories. Within each category, we list example effects that we incorporated into functional demo applications. These demonstrative scenes serve to showcase the diverse expressivity and technical feasibility of our haptic suit, but this list is not exhaustive and there are many other creative effects that we did not have time to implement.

Figures 11 through 20 offer screenshots and illustrations of our various haptic effects, and Figure 21 provides a breakdown of the effect parameters in each scene. It is impossible to adequately capture the richness of the rendered effects through still figures, so we strongly encourage readers to also refer to our Video Figure.

5.1 Vibrations

As already discussed, our suit can render both vibrotactile and kinesthetic effects. As vibrotactile effects are already extensively used in VR/AR, both in research and consumer systems, we focus most of our discussion on kinesthetic effects.

5.2 Static Forces

Starting with the most straightforward force effect, we can command our motor reels and string mechanisms to generate *persistent* and *constant* forces. Our demo applications include the following haptic effects:

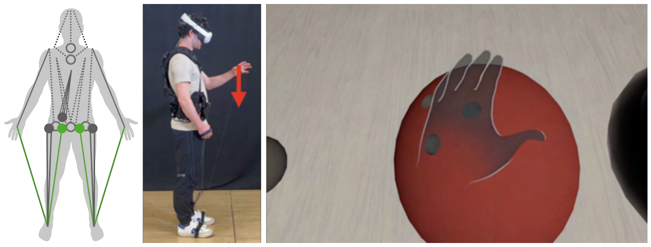


Figure 11: In this example scene, the user stands in front of a table with three objects: a pool ball, a bowling ball, and a cannonball. If the user picks up these objects, the hand is pulled downwards with 5N, 20N, and 35N of force respectively. The user can also drop these items into their VR backpack, and we cumulatively increase the force. The back pulley system has 3× mechanical advantage, so the user can place all three balls in the backpack with a combined force of 60N.

Figure 12: In this example scene, the user finds themselves on different alien planets with varying levels of gravity. To simulate this, we command most motor reels (other than hand upwards and head left/right) to statically pull at 10 or 20N. This has the effect of downward compression, encumbering user movement.

Object Weight - When a user holds a virtual object in the hand, we pull the corresponding hand downward with an appropriate force (potentially the actual weight of the object, but we found the relative weight between objects to be more important than the absolute force). We also simulated the weight of items carried in a backpack by loading up the user's back (Figure 11).

Gravity - A similar effect that acts on the whole body is increased gravity (Figure 12). To simulate this, we tighten all reels with a downward component, significantly loading the user's musculature.

5.3 Dynamic Forces

This category contains forces that are *persistent* and *varying*, most often linked to a dynamic value of an object or effect in a VR scene (the velocity of a vehicle, the rate of water flow from a faucet, etc.). Our demo scenes include the following example forces:

Force from Linear Acceleration - Our first example is force from linear acceleration, such as a spaceship (Figure 13) or a car (Figure 14) accelerating forward. In our example scenes, we simulate this force effect by pulling back on the user's head and back, proportional to the acceleration.

Centripetal Force - Centripetal forces are felt when there is a change in direction, for instance, when turning a corner in a moving car (Figure 14). The magnitude is proportional to the rate of angular change. For this effect, we can load up the head and legs on the appropriate side of the user's body.

Compression Force - Kinethreads can simulate some compression forces, simply by loading the appropriate part of the body. For example, we compress the front and back of the torso at high force to create the feeling of being cinched tight with a rope (Figure 15). This effect could also be used to create the feeling of being squeezed, for instance when diving deep in water. By using a bell-curve-shaped force function, timed and applied to the legs, it is possible to simulate the feeling of landing on a virtual trampoline. This could also be used to simulate weight training, i.e. loading up the legs while the user is doing squats.

Normal Force / Force Feedback - Our system has limited ability to simulate force feedback (i.e., contact with objects). To match reality, our system would have to resist forces the user applies to virtual surfaces with equal and opposite force. However, our system does not have the capability to render many directional force vectors. For the hands, where force feedback is most commonly encountered,

Figure 13: Seated in a spaceship, the user accelerates out of a launch tube towards an alien planet. The suit pulls on the user's head and back to simulate linear acceleration, while the abdomen, legs, and head vibrate from the launch.

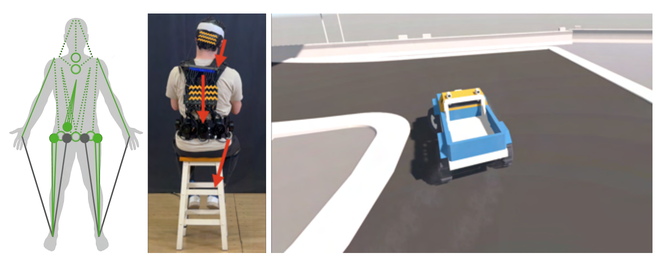


Figure 14: In this car racing game, the user's head is pulled left and right, proportional to the centripetal force. We also load up the legs (simulating the weight of the body shifting) proportional to the centripetal force. The head and back are pulled backwards with the car's acceleration, while engine vibrations are rendered to the abdomen, hands, and head.

Figure 15: In this Wild West setting, the user has been captured by a bandit and is being tied up and cinched tight with a rope, compressing the abdomen, back, arms, and legs.

Figure 16: In this dungeon scene, the user, playing as a wizard, attempts to extinguish a fire by casting an Aguamenti charm. The user can control the flow rate with their left hand, and the right (emitting) hands feels a proportional reaction force overlaid with vibrations from the water stream.

we can reasonably simulate contact with vertical surfaces (walls, doors, etc.) by using the string vector that extends from the shoulder to the palm to arrest the hands. However, we cannot realistically simulate most horizontal surfaces (tables, shelves, keyboards, etc.) because we do not have a true up vector. If the hand is low and closer to the waist, the best our suit can do is utilize the same shoulder vector to pull roughly upwards. Therefore, normal forces can only be rendered for a subset of object placements, and future work is needed to more fully emulate this haptic effect.

Reaction Force - Some objects and interactions create long-duration reaction forces, such as a wizard casting a spell (Figure 16) or a fire hose shooting water. For this, we pull the hands back towards the body with force proportional to the rate/flow of the effect.

5.4 Impulsive Forces

A particularly common and useful category of forces in VR are impulse effects, typified by their *short durations*. Our demo scenes included the following haptic events:

Object Collision - When a user is hit by an object, there is a brief impulsive force imparted from the collision. Examples include getting punched while boxing (Figure 17) or hitting a ball with a racket (see Video Figure).

Recoil Force - This is a short-duration reaction force (see above), most often associated with firing a weapon.

Explosive Force - Explosions, which are generally large in magnitude, are impossible to accurately simulate without harm to the user. Nonetheless, we found that briefly actuating all of our motors at maximum force (Figure 18) was reasonably immersive.

5.5 Force Animations

As a final category, we have force animations. These do not dynamically vary their output in response to a value in the VR scene, but instead are pre-authored and "played" (i.e., not parameterized). We found these to be a useful and immersive design primitive.

Environment-Bound Animations - Force animations can be triggered by the user's environment. Examples we built include the swaying and rumbling vibration felt in a train car (Figure 19), as well as being buffeted by water while standing under a waterfall (Figure 20). In both cases, we consider these to be environment-bound effects — played when the user enters a zone.

Object-Bound Animations - Instead of attaching animations to zones in the environment, it is also possible to have haptic animations play when interacting with an object (touching, holding, riding, etc.). For example, leaning against a running (vibrating) engine, holding a ticking time bomb, or riding a skateboard.

Social Touch Animations - A special sub-category of object-bound animations are human-bound social animations. These include events such as handshakes (see Video Figure), hugs, and high fives, which can be approximated by our suit.

Figure 17: In this boxing game, the user receives left and right hooks to the head, uppercuts, and punches to the hands and abdomen, with corresponding body zones receiving high-force impulsive haptic events.

Figure 18: In this Wild West scene, a stick of dynamite is lit, leading to an explosion that renders a full-body, impulsive haptic event.

Figure 19: In this runaway train scene, the user sways back and forth in sync with the train car visuals. For this, we load up the left or right legs proportional to the lean of the train, simulating the user's body weight shifting. We also load the abdomen and back with the absolute value of the sway force. Finally, we add a 60Hz vibration to the hands, head, legs, abdomen, and back, conveying the shaking of the train car at high speed.

Figure 20: The user is free to move around this tropical island environment. When standing under or walking through the waterfall, the user is buffeted by the falling water. We render this by pulling on the arms, head, abdomen, back, and legs with randomly generated forces (between 10 and 40N) and for random periods of time (40-1000ms), independently for each body zone. These desynchronized haptic effects effectively convey the chaotic turbulence of falling water, and superimposed on top are 25 and 50Hz vibrations.

6 User Study

To gather feedback on the haptic stimuli we are capable of rendering, as well as to evaluate the realism and immersion of kinesthetic haptics vs. vibration effects, we ran a user study with ten haptically diverse example scenes.

6.1 Procedure

For the user study, participants were located in a small office, and the experimenter helped them put on the vest and VR headset. Participants were presented with all 10 scenes described and pictured in Section 5 (Figure 21 details the specific haptic parameters used), and the scenes were presented in a randomized order. Each scene was experienced four times with four haptic conditions: No Haptics, Vibration Haptics, Kinesthetic Haptics, and Vibration & Kinesthetic Haptics. In our No Haptics condition, the users still wore Kinethreads, but the motors were turned off. The order in which the haptic conditions were presented was randomized per participant. No Haptics and Vibration Haptics can be considered baseline conditions, as these are the most common experiences in contemporary VR: bare hands operation (No Haptics) and controllers (Vibration Haptics).

We recruited 12 participants (mean age 26.5, 7 identified as male, 4 identified as female, 1 identified as non-binary) who were compensated $20 for the 60-minute study. The participants' experience with VR ranged from never having used a headset before, to using VR weekly for fun. Most of the scenes were experienced while standing and participants were allowed to move around freely; participants sat on a stool for the spaceship, train, and car racing scenes. When first loaded into each scene, participants were given a brief introduction to the setting and interaction, and they could repeat it as many times as they wished. For each scene, all four haptic conditions were shown, one after another. After each haptic condition, the participant completed the inter-trial questionnaire in VR (see Section 6.2), answering out loud (the experimenter recorded the answers). At the end of the study, the participant removed the Kinethreads vest and headset and answered the post-trial questionnaires using paper and pen.

6.2 Feedback Questionnaires

We chose standard questionnaires modeled after prior work [18, 53, 54] for evaluating our four haptic conditions. Specifically, after each condition in each scene, the participant was shown a five-question

Demo Scene	Force Interaction	Force Category	Hands ⬆	Hands ⬇	Legs	Abdomen	Back	Head ⬇	Head ⬅➡
Held Objects & Backpack	Object Weight	Static	-	Per-Object Preset F (5, 20, 35N)	-	-	Per-Object Preset F (10, 30, 60N)	-	-
Alien Planet	Gravity	Static	-	Per-Planet Preset F (10, 20N)	Per-Planet Preset F (30, 60N)	Per-Planet Preset F (25, 50N)	Per-Planet Preset F (45, 90N)	Per-Planet Preset F (8, 16N)	-
Spaceship Launch	Linear Acceleration	Dynamic	-	-	F ∝ Velocity [0-80N] V: 100Hz	V: 100Hz	F ∝ Velocity [0-100N] V: 100Hz	F ∝ Velocity [0-17N] V: 100Hz	-
Car Racing	Centripetal Force, Linear Acceleration	Dynamic	V ∝ Velocity [30-80Hz]	-	F ∝ Angular Vel. [0-80N] V ∝ Velocity [30-80Hz]	V ∝ Velocity [30-80Hz]	F ∝ Velocity [0-110N] V ∝ Velocity [30-80Hz]	F ∝ Velocity [0-17N] V ∝ Velocity [30-80Hz]	F ∝ Angular Vel. [0-17N] V ∝ Velocity [30-80Hz]
Tied Up by Bandit	Compression	Dynamic	F ∝ Rope Diameter [0-40N]	-	F ∝ Rope Diameter [0-80N]	F ∝ Rope Diameter [0-50N]	F ∝ Rope Diameter [0-100N]	-	-
Wizard Spellcasting	Reactive	Dynamic	F ∝ Distance [0-40N] V ∝ Distance [0-150Hz]	-	-	-	-	-	-
Boxing	Object Collision	Impulse	F: 40N V: 25Hz	-	-	F: 50N V: 25Hz	-	F: 17N V: 25Hz	F: 17N V: 25Hz
Dynamite Explosion	Explosion	Impulse	F: 40N V: 50Hz	-	F: 80N V: 50Hz	F: 50N V: 50Hz	F: 120N V: 50Hz	F: 17N V: 50Hz	-
Waterfall	Object-Bound Animation	Animation	-	F: [10-40N] for 40-1000ms (random), V: 25Hz	F: [10-80N] for 40-1000ms (random), V: 25Hz	F: [5-50N] for 40-1000ms (random), V: 50Hz	F: [10-100N] for 40-1000ms (random), V: 50Hz	F: [2-10N] for 40-1000ms (random), V: 50Hz	-
Runaway Train	Environment-Bound Animation	Animation	-	V: 60Hz	F ∝ Train Sway [0-60N] V: 60Hz	F ∝ Train Sway [0-50N] V: 60Hz	F ∝ Train Sway [0-80N] V: 60Hz	V: 60Hz	-

Figure 21: Overview of the kinesthetic (red text) and vibration (orange text) effects used in the ten scenes from our user study.

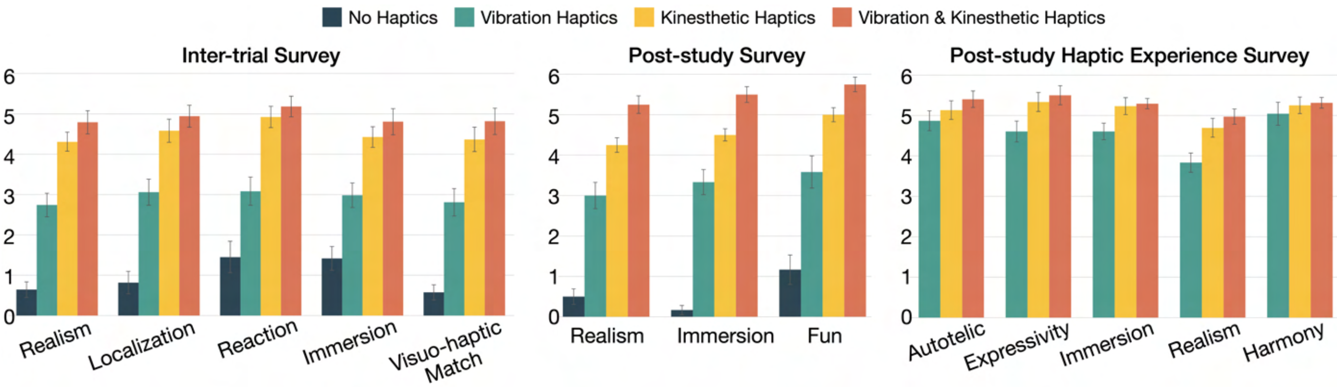


Figure 22: The Likert results from our three user study questionnaires (normalized to range 0-6): the inter-trial survey (left), the post-study survey (middle), and the Haptic Experience survey [49] (right). Error bars are standard error.

inter-trial survey: 1) The feeling of the virtual object was realistic. 2) It seemed as if I felt the virtual object in the location where I saw the virtual object. 3) When the interaction happened, I felt the instinct to react. 4) I felt immersed. 5) The sensation felt matched to the graphics. All questions were answered with a seven-point Likert scale ranging from strongly disagree (1) to strongly agree (7). The questions and the Likert scale were displayed in a VR scene so the participant would not have to remove their headset.

Once the participant had finished experiencing every scene, they answered two final question sets. The first was a 12-question post-study survey modeled after prior literature [18, 54]: 1) The no haptic feedback examples felt realistic; 2) The vibration-only feedback examples felt realistic; 3) The pull-force-only feedback examples felt realistic; 4) The both haptic feedback examples felt realistic; 5) The no haptic feedback examples made me feel more immersed in the scene; 6) The vibration-only feedback examples made me feel more immersed in the scene; 7) The pull-force-only feedback examples made me feel more immersed in the scene; 8) The both haptic feedback examples made me feel more immersed in the scene; 9) The no haptic feedback examples were fun. 10) The vibration-only feedback examples were fun. 11) The pull-force-only feedback examples were fun. 12) The both haptic feedback examples were fun. Participants also ranked the four haptic conditions from most to least preferred. Finally, participants filled out the 22-question Haptic Experience survey from Sathiyamurthy et al. [49] for the three active haptic conditions (Vibration Haptics, Kinesthetic Haptics, and Vibration & Kinesthetic Haptics).

6.3 Results

The results from the questionnaires can be seen in Figure 22. For the inter-trial survey, the Vibration & Kinesthetic Haptics condition uniformly outperformed the other three haptic conditions, followed by Kinesthetic Haptics, Vibration Haptics, and then No Haptics, which was rated substantially less than the other haptic conditions. A repeated measures ANOVA (df=11) followed by Holm-Bonferroni-corrected pairwise comparisons revealed that the Vibration & Kinesthetic Haptics condition significantly outperformed No Haptics, Vibration Haptics, and Kinesthetic Haptics ($p<0.001$ for all pairwise comparisons). The category with the largest difference in scores between Kinesthetic Haptics and Vibration Haptics is Reaction, which may be because kinesthetic forces are much larger than vibrotactile ones, and therefore more likely to elicit a reaction from the user.

The results of the first post-study survey also closely follow that of the inter-trial survey, with the Vibration & Kinesthetic Haptics condition achieving the highest rating. Statistical testing showed the same results as the inter-trial survey, where a repeated measures ANOVA (df=11) followed by Holm-Bonferroni-corrected pairwise comparisons revealed that the Vibration & Kinesthetic Haptics condition significantly outperformed all other haptic conditions ($p<0.001$ for all pairwise comparisons). In our ranking task, all participants ranked the Vibration & Kinesthetic Haptics condition as the most preferred, and all but one put Kinesthetic Haptics as second and Vibration Haptics as third, with one participant flipping that order.

Finally, the haptic experience survey has participants individually considering each active haptic condition and answering questions along five categories. For this survey, a repeated measures ANOVA (df=11) followed by Holm-Bonferroni-corrected pairwise comparisons indicated that Vibration & Kinesthetic Haptics was ranked significantly higher than Vibration Haptics ($p<0.05$) but was not significantly different from Kinesthetic Haptics ($p>0.05$), suggesting that kinesthetic haptics in general were beneficial to the haptic experience. The largest difference is in realism, indicating that in the varied interactions we chose for our example scenes, kinesthetic forces are more necessary to approximate reality. Kinethreads performing significantly better than the baseline conditions throughout different questionnaires indicates that not only does our combined capabilities of kinesthetic and vibrotactile haptics create a better experience than either modality alone, but also that our system can successfully render a broad, diverse set of demo scenes.

7 Discussion & Limitations

7.1 Force Design Configuration

The primary limitation of Kinethreads is the inability of our actuation method to render forces away from the user; i.e., our haptic exosuit can only pull on a user's limbs, not push. This is because strings can only apply tension in one direction, and the inherent flexibility of the strings prohibits being able to push force the other direction. This is a common functionality of rigid exoskeletons that Kinethreads cannot emulate, therefore inherently limiting our set of expressive forces. For example, our suit is incapable of producing external forces that pull on the body, like if the user were to draw a bow in VR or resist a dog tugging on his leash. In some of our implemented example scenes, like when users experience gravity on alien planets, we were unable to render a downward force on the legs. This force vector would require motors anchored to the ground, tethering our suit to the environment, meaning it would no longer be stand-alone or wearable. However, we found in our pilot testing that by pulling upwards on the legs, combined with convincing visuals and other appropriately rendered forces on the body, user immersion was preserved in this scene.

7.2 String Routing

Another limitation of Kinethreads is that the strings actuating the hands must travel through mid-air to achieve the appropriate pull force vectors. Though our control software actively minimizes string slack and tries to maintain tension, these strings could still snag on objects in the environment or on the suit itself. A potential solution would be to route the strings directly along the limbs, using cable housings that sit flush with the user's skin on long sleeves and pants (similar to CRUX [32] and some other soft exosuits; see Section 2). However, not only would this make the exosuit more difficult to don, but this would also significantly change the force vectors — for example, it would be impossible to render a downwards pull on the hands, crucial for effects such as conveying the weight of a held object.

7.3 Perceptual Mismatches

A consequence of our form factor is that routing string mechanisms across the body using pulleys introduces residual force artifacts that are felt at the pulley locations in addition to the intended actuation site. Fortunately, these secondary forces are often subtle due to the body's sensitivity bias towards our limbs, and many of the motors and pulleys are mounted along the torso and shoulders. The largest perceptual mismatch comes from the downwards hand vectors being routed through the feet, the only extremity-to-extremity routing we use. This means that sometimes effects that pull down on the hand can create a noticeable upwards force on the foot, like holding a cannonball. Future work could include design configurations exploring pulley placements that minimize these extraneous forces, while preserving similar force vectors.

Similarly, vibration effects also occur at the motors, pulleys, and anchor points. This could lead to a perceptual mismatch if only the anchor point should be feeling the vibration (i.e., if the user is holding a vibrating object, but they can also feel the vibration on their feet and hips due to the string routing). As stated above, these vibrations on the body are much less noticeable than on our extremities (hands, feet, head). In practice, we designed example scenes where the vibration effects across the body were perceptually matched, like the user feeling the vibration of the steering wheel while driving, but also feeling that vibration on the body because they are sitting in a car.

7.4 Latency Tradeoff

There are two main sources of latency in Kinethreads. The first is latency from the pulley mechanisms, as described in Section 3.6.8. The more mechanical advantage provided by the pulley, the more length of string is used, and the more time it takes to reel in, increasing the latency of the haptic effect. This is an inherent limitation of pulleys, and so future exosuits using these motor-pulley mechanisms will have to take this latency into consideration, weighing the tradeoff between mechanical advantage and latency in their design.

The second source of latency comes from string slack; if there is excess string when a haptic effect is triggered, then the motor will have to reel that slack in before the user can feel the pulling effect. For instance, if an explosion effect is only rendered for 200ms and there is a lot of slack in the string, the user may not feel the effect, as only the excess string would be reeled in during that time. To solve this issue, we implemented auto-reeling (Section 3.4), which reels in until there is slight resistance from the user, and then discontinues — the user feels a very subtle tug when this happens. The frequency of auto-reeling can be tuned from once every few seconds to continuous, where continuous auto-reeling will have no string slack latency but will cause a subtle, constant pull on the anchor points. The tradeoff is between how often the system tugs and how much latency is introduced by unretracted slack.

8 Future Work

To minimize cost while maximizing body coverage, Kinethreads targets haptic effects on important limbs, allowing for full-body actuation with the minimum number of motors. Future work could easily add more individually actuated zones on the body using the same Kinethreads reel mechanisms. However, this would necessitate a proportional increase in motors, adding cost, weight, and complexity. Kinethreads serves as a platform to investigate the potential of motor-pulley mechanisms in rendering kinesthetic haptic forces; alternate design configurations could easily emphasize different body parts or wearable form factors using these same mechanisms. To facilitate replication, we have open-sourced our design: https://github.com/FIGLAB/kinethreads.

Beyond push forces, other force profiles may be theoretically feasible with our actuation method, such as elastic forces, buoyancy effects, drag forces rendered across the body, or more fine-grained textures by modulating contact friction force. Future work could explore these possible force types, as well as further explore different reel placements for perceptual manipulation of intensity, directionality [10], realism, and body-zone sensitivity.

Finally, although Kinethreads significantly reduces cost compared to prior systems, the bill of materials was still around $400, with motors comprising 75% of this cost. To further reduce cost, future work could explore cheaper, smaller motors paired with high-ratio mechanical advantage pulleys, enabling similar force rendering at a fraction of the cost.

9 Conclusion

In this work, we introduced our full-body haptic exosuit, called Kinethreads, which delivers powerful, distributed force feedback in a wearable, flexible, lightweight, and affordable form factor using motor-pulley mechanisms. This exosuit can bridge the gap between low-cost consumer haptics and high-performance exoskeletons, taking advantage of motor reels that can deliver both kinesthetic and vibrotactile effects. Through a series of technical performance characterizations and a user study evaluating our system's expressive capabilities, our work highlights a promising direction for expanding the realism and accessibility of full-body haptic feedback in virtual and augmented experiences.

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