A Novel Variable-Stiffness Finger Exoskeleton for Virtual Reality Applications

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A hand exoskeleton that can produce forces in both flexion and extension, as well as provide a variable stiffness to the wearer, finds applications in virtual reality (VR). In VR, the objective is to convince the user that a given experience is real; part of this process involves providing realistic force- and tactile-based sensations to the user when they interact with virtual objects. We propose a novel hand exoskeleton that can provide forces comparable to other state-of-the-art exoskeletons while also adding the ability to vary stiffness. Additionally, our mechanism improves wearer comfort by producing for a two-stage actuation process—translation then rotation—which allows the exoskeleton to closely track the wearer's joints. In VR applications where the user interacts with soft objects, the ability to modulate perceived stiffness is paramount to producing a believable experience.

1 Introduction

In recent years, virtual reality (VR) technology has proliferated: there are several commercial VR headsets currently available—the Oculus Quest, HTC Vive, Valve Index, and Sony Playstation VR—and more are released every year. Modern research is primarily focused on hand and body tracking, with the hope that such technology enables increasingly immersive gaming and media experiences.

While many believe that widespread adoption of VR technology is around the corner, there are many difficulties currently facing the field. Users have expressed discomfort regarding the apparent disconnect between the real world and the virtual world presented to them by their headset: when the virtual experience isn't entirely accurate, people experience irritation due to their expectations of the physical world not being fully met. To some degree, this problem can be remedied by realistic physical simulations in VR—rigid objects should collide elastically, rotate with conserved momentum, and fall at 9.8 m/s^2, just as we expect them to.

While vision plays a large role in producing believable experiences, VR users' belief is shattered when they attempt to physically interact with virtual objects. Many applications require the user to grasp things; if the user closes their hand around a virtual cube, as depicted in figure 1, they expect to feel tactile sensations and reaction contact forces. Inevitably, they don't, leading to a cognitive dissonance between their visual senses and their tactile senses.

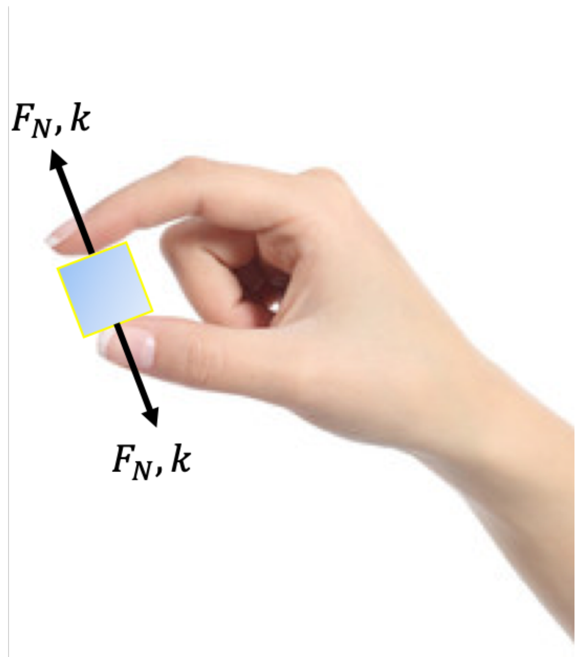

Fig. 1. A typical scenario in virtual reality: the user grabs a virtual cube and expects to feel a reaction force F_k and a stiffness k.

The lack of force- and tactile-based feedback makes *fine object manipulation* in VR difficult. Human hands are most precise when relying on environmental *contact forces*: if someone is manipulating a detailed object, they rely on the rigidity of the object to define acceptable locations for the fingertips to exist. For video games, this problem is of low consequence. For academic and enterprise applications, this problem is significant. Recently, VR has found use in surgery simulation: where surgical training has historically been one of apprenticeship, where the trainee is taught under the supervision of a trained surgeon, virtual reality surgery simulation promises to reduce the training time, cut down on costs, and improve the efficacy of the training procedure [1] [2].

For these reasons, we propose a novel variable-stiffness finger exoskeleton to provide detailed force feedback and model environmental contact forces in virtual reality applications. Unlike other exoskeletons, we place a strong emphasis on having a small and non-invasive form factor, so as to produce minimal fatigue in the wearer's hand. Additionally, we introduce a novel mechanism that provides variable flexion stiffness to the wearer.

2 Related Work

Hand exoskeletons can be categorized in several ways. Designs differ in terms of actuation—active devices can be driven by electric [3], pneumatic [4], or shape-memory-alloy (SMA) [5] motors—as well as other qualities, such as material and number of degrees of freedom. One of the greatest sources of variance in hand exoskeleton designs, however, comes from the mechanisms used to transmit torques to the finger joints. For the most part, the force transmission component of hand exoskeletons fall into four main categories: cable-based, linkage-based, soft (pneumatic- and SAM-type actuators), and sliding-spring-based (hybrid rigid-soft designs). It is along these lines that this section is divided.

2.1 Cable-based exoskeletons

Since human fingers are essentially planar 3-link kinematic chains [6], a sensible solution for force transmission is to attach an externally actuated 3-link chain with matched joint centers. This configuration lends itself to cable-based actuation, since pulleys placed concentrically with the joints can be directly driven to move the wearer's fingers. Worsnopp et al. (2007) [7] propose an actuated finger exoskeleton intended to provide independent control of all three joints of the index finger. They directly actuate the joints using a hybrid cable and gearing system. Hasegawa et al. (2008) [8] introduce a tendon-based assertive device that actuates the wearer's joints directly. Using a custom actuator unit, their exoskeleton is compliant and able to be back-driven, allowing for safe operation as well as force-based control.

More recently, Marconi et al. (2019) employ this method in their development of HandeXos-Beta (HX-β), a thumb-finger exoskeleton for hand rehabilitation [9]. HX-β contains several innovative features: it independently actuates thumb flexion/extension and circumduction, and it uses a series elastic element to control force output. A disadvantage to all cable-based devices is that the cables can only transmit forces in tension, meaning twice as many cables are needed as degrees of freedom, leading to design complexity. Additionally, mounting a linkage to the side of the wearer's finger (as opposed to the top or bottom) adds bulkiness to the device, leading to a sub-optimal form factor.

2.2 Linkage-based exoskeletons

To solve the problems caused by a bulky side-mounted kinematic chain, many exoskeletons rely on sophisticated top-mounted mechanical linkages to transmit torques to the off-axis finger joints. With HEXOSYS, Iqbal et al. (2010) [10] use a serial chain mounted on the top of the hand to specify the location of the thumb and index finger proximal phalangeal bones. By driving one end of the linkages, they are able to press and pull on the fingertips. Fontana et al. (2009) [11] use a set of 6-bar linkages to rigidly transmit torque about a remote center of rotation aligned with the wearer's joints. While they reduced bulk on the sides of the finger, their mechanism occupies a good deal of space on the top of the hand. To address the problem of form factor, Cui et al. (2015) [12] designed a low-profile, 3D-printable five-fingered robotic hand exoskeleton for rehabilitation. Each finger is underactuated and driven by an electric linear actuator. Linkages for hand exoskeleton actuation have the advantage of being able to rigidly transmit high forces, but they are often complex and massive, adding complexity and weight to a device that is often intended to be lightweight and mobile.

2.3 Soft exoskeletons

The design of soft exoskeletons is inextricably linked to the design of the soft actuators that power them. Kadowaki et al. (2011) [13] developed a power-assist glove for hand grasping in daily life, actuated by pneumatic rubber muscles. This device was the successor to a grasping glove developed by Sasaki et al. (2004) [14], which also used pneumatic rubber muscles to provide joint torques. Ang et al. (2017) [4] propose PIY Glove, a 3D-printed pneumatically-actuated hand exoskeleton. PIY Glove uses a novel, fold based design of 3D printed soft actuators to achieve bending motion in the fingers. Dittmer et al. (1993) [5] take a different approach, actuating their exoskeleton glove using a shape memory alloy. While soft exoskeletons have the advantage of having simple, low-profile designs, the soft nature of their actuators inherently limits the amount of force and stiffness they can output. This makes them not ideal for rapid or high-force applications.

2.4 Sliding-spring-based exoskeletons

Arata et al. (2013) [3] propose an innovative method for force transmission using a sliding spring mechanism. Essentially, a piece of sheet metal is fixed to the end of the fingertip of the exoskeleton, and slides through the other joints. As it is pushed through, it forces the entire linkage to bend. Li et al. (2019) [15] further developed this idea, using a steel strip to transmit force through a multi-segment hybrid rigid-soft mechanism. The sliding spring acts as a cable in tension, but is rigid in compression as well, allowing for high output force capacity while maintaining a small form factor. In terms of transmitting torques, however, the spring is much stiffer in flexion than in extension, making such mechanisms not ideal for rigidly actuating the hand in both directions.

Our contributions We propose a novel hand exoskeleton that externally actuates the wearer's fingers. Similar to [3] and [15], we use a sliding spring mechanisms to convert force from a linear actuator into torques about the wearer's finger joints. Unlike previous works however, our device has a cable- and spring-based mechanism that adds inverse cur-

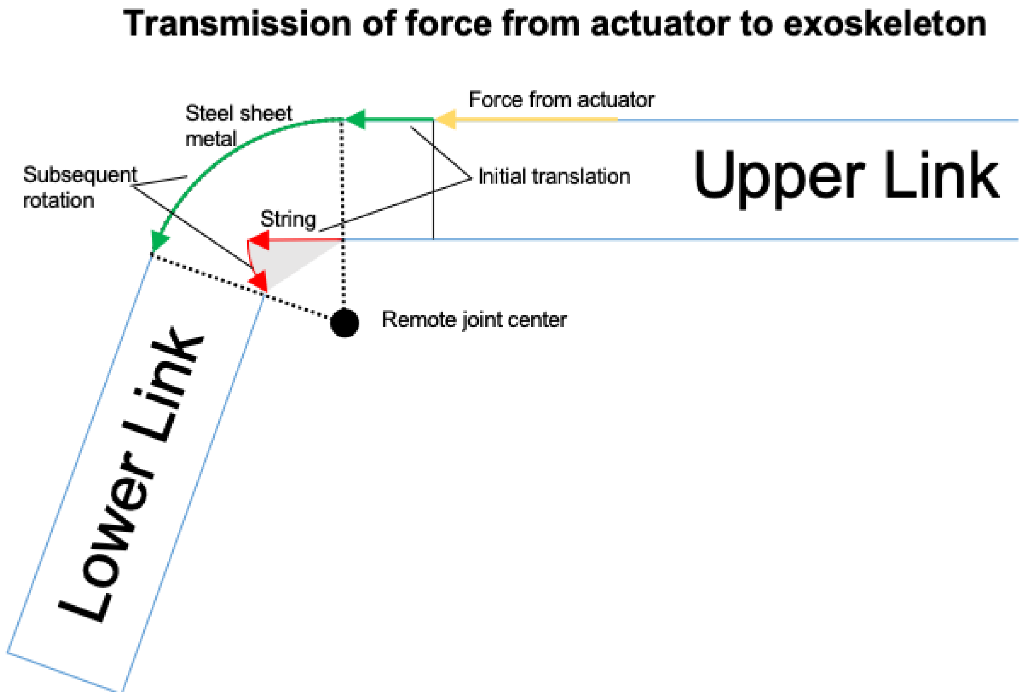

Fig. 2. Diagrammatic depiction of the actuation process shown in figure 6. The actuator applies a force (yellow) to the steel sheet metal (green). Initially, the string (red) is not taut and both the sheet metal causes the lower link to translate. Once the string becomes taut, the sheet metal is forced into an arc, and the lower link rotates about the indicated remote joint center. During this latter process, the string traces out an arc (solid grey) centered at the lower left corner of upper link.

vature to each joint, making it stiff in flexion as well as in extension. Additionally, by varying the tension in the cable attached to the spring, the flexion stiffness can be varied.

3 Primary Mechanism Architecture

Inherent in the goal of producing a comfortable and functional exoskeleton is requirement that the device seamlessly follows the wearer's fingers as they undergo flexion and extension. As noted in the previous section, this is achieved in one of two ways: by co-locating the center of the mechanism with the center of the wearer's finger joints, or by designing a mechanism that rotates about a remote joint center.

In the name of a minimal form factor, we decided that our exoskeleton should reside entirely on the top of the wearer's hands, and not occupy space between their fingers. Having observed the movement of the skin on the tops of fingers during flexion, it became apparent that a top mounted mechanism would need to account for both translation and rotation. We achieved this by designing a mechanism to enable these two regimes of movement and actuation. Figure 2 shows the primary design of the mechanism (note: it does not show the inverse stiffness spring, which will be discussed later). The mechanism consists of two links: the upper link is rigidly connected to the linear actuator as well as one side of a finger joint; the lower link is fastened to the other side of that same finger joint.

Both the upper and lower link can be approximated by

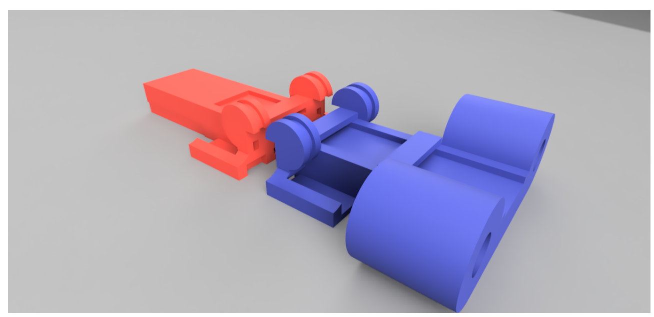

Fig. 3. Rendering of the two parts of the mechanism that sit on opposite sides of a finger joint. A piece of steel sheet metal slides through the channel in the blue piece and anchors into the corresponding channel in the red piece. The circular sections serve as pulleys to route the string. The small channel on the side holds the inverse stiffness spring.

rectangular boxes with identical cross sections. The upper edge of these boxes is connected by a piece of steel sheet metal (0.3mm thick, 8mm wide), which slides with respect to the upper link but is fixed rigidly to the lower link. The lower edge of these boxes is connected by a string. This allows for two distinct regimes of operation: one where the string is not taut, and the other where it is.

The actuation happens in two stages, as depicted by the two sets of red and green arrows in figure 2. First, the actuator pushes the steel sheet metal through the channel in the upper link of the mechanism. Since the string is not yet taut,

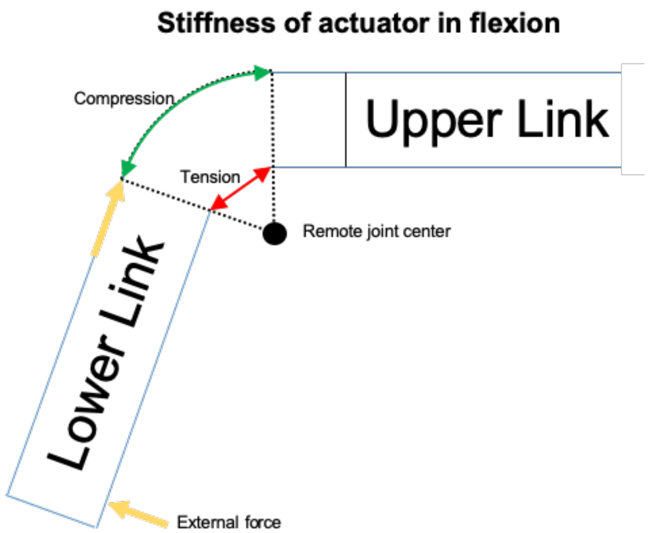

Fig. 4. Depiction of the flow of forces under an external force trying to extend the exoskeleton. The steel sheet metal (green) acts as an arch under compression, making it very rigid. The string (red) remains in tension.

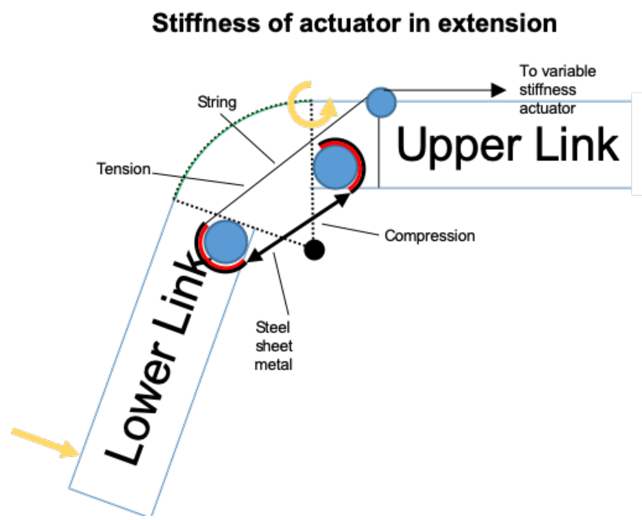

Fig. 5. Depiction of the flow of forces under an external force trying to flex the exoskeleton. Without the addition of the inverse stiffness spring, the string would be under compression where it would immediately buckle and the sheet metal (green) would bend around its attachment point to the upper link. Instead, flexion loads are transmitted to the inverse spring (thick black) which acts under compression. The level of engagement between the lower link and the friction pad (red) of the inverse spring is controlled by the tension in the string (thin black).

the lower link undergoes pure translation with respect to the upper link. This can be seen in figure 6, between stage (1) and stage (2). Once the string becomes taut, any subsequent linear force applied by the actuator forces the sheet metal to travel along an arc, and the lower link rotates about a remote joint center. With the link lengths chosen appropriately, the remote joint center aligns with the wearer's finger joint.

3.1 Flexion Stiffness Analysis

In order to apply high forces in flexion, it is necessary that the mechanism be properly stiff and not allow great displacements if the user resists the motion. Not only would such displacements reduce the realism of the VR experience of grabbing a rigid object, but it would perturb the location of the remote joint center about which the exoskeleton flexes. Primarily, users of VR are concerned with *grabbing* virtual objects, meaning they will expect to feel contact forces compelling their hand into *extension*. However, it is sometimes the case when undergoing dexterous motion that the user experiences contact forces that resist extension, in which case it becomes important to impose rigidity in the flexion direction as well.

Our mechanism was naturally much stiffer in flexion than in extension. As shown in figure 4, an external force (yellow) attempting to extend the exoskeleton would be transferred to the steel sheet metal (green) in the form of compression. In this configuration, the sheet metal acts as an arch, which, assuming it doesn't buckle, is incredibly rigid under compression. The string, in this case, is forced into tension, a regime in which the string is naturally very strong and rigid.

4 Inverse Stiffness Mechanism

While our mechanism was naturally stiff in flexion, it was also naturally *not* stiff in extension. This was unfortunate, given the importance of extension stiffness for VR applications. Under the influence of an external force compelling the exoskeleton into flexion, all the stress on the steel sheet metal became concentrated in the line where it contacted the upper link. This stress concentration is indicated by a circular yellow arrow in figure 5. The string contributed nothing to the extension stiffness, given that it was forced into compression under external flexion loads.

To remedy this problem, we devised a secondary mechanism, an *inverse stiffness mechanism*, which greatly increased the extension stiffness of our exoskeleton. Essentially, we add four cylindrical sections to the mechanism, two for each link and one on each side. The cylindrical sections are 6mm in diameter, 3mm thick, and centered at the edge of each link (the edges facing the other link). These cylinders are indicated by the large blue circles in figure 5. Additionally, they can be seen in the CAD rendering of our mechanism, figure 3, as well as figure 6, which shows our exoskeleton in action.

To connect the cylinders on opposing links, we fabricate a thin piece of steel sheet metal that contains semi-circular hooks on either end. We embed a small piece of rubber inside each hook to increase the friction between it and the cylindrical anchors. The hook connected to the upper link is fixed into place. The other end of the sheet metal is able to slide freely through the lower piece. Note that this configuration of hook and cylinder is identically replicated on both

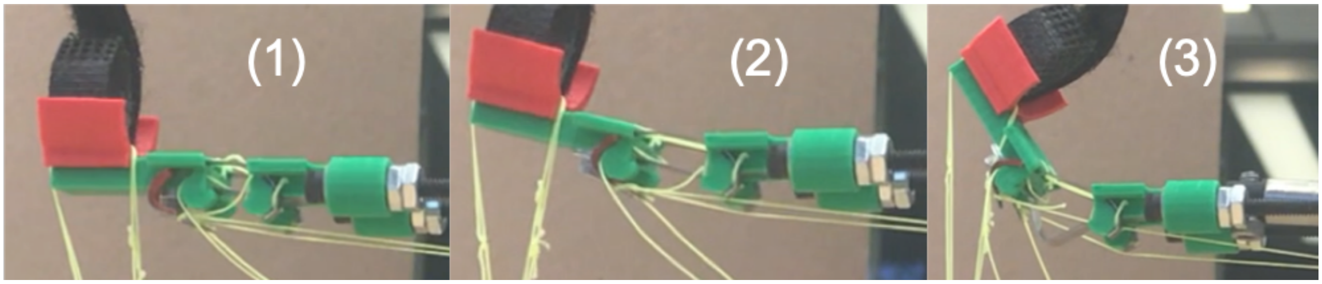

Fig. 6. The three states, corresponding to two stages, of the actuation process. In (1), the mechanism is in its most collapsed form and the string is not taut. The linear actuator pushes on the lower link (on left), which purely translates until the string becomes taut (2). Subsequent force applied by the linear actuator forces the mechanism to purely rotate (3) about a remote joint center.

sides of the exoskeleton.

The sequence of actuation then became: 1) the string starts not taut, the lower hook does not contact the lower cylinder. 2) The actuator pushes the steel sheet metal and the lower link purely translates; at the same time the string becomes taut, the lower hook contacts the lower cylinder. 3) The actuator continues to push and the lower link enters the rotation regime; the lower hook remains in contact with the lower cylinder. When the lower hook contacts the lower cylinder, they theoretically lock rigidly with one another. In this case, the external perturbation force on the lower link gets rigidly transmitted to the lower hook, which in turn forces the inverse stiffness spring into compression, in which case the entire exoskeleton becomes rigid.

In order to guarantee that the lower cylinder and lower hook become fixed with respect to each other, we add a tensioning string, the *inverse stiffness string*, to the top of the hook. This string is routed to a pulley on the upper link. When the inverse stiffness string is pulled taut, the friction pad of the hook is forced against the lower cylinder, forcing the two to become locked. As an added consequence of this mechanism, we determined that it is theoretically possible to vary the extension stiffness in the lower link by varying the tension in the inverse stiffness string.

5 Results and Discussion

The testing procedure of the exoskeleton was two-fold: first, we tested whether the geometry and dynamics of the mechanism behaved as predicted; second, we quantitatively characterized the performance of the actuator in providing contact forces and we qualitatively determined its ability to produce flexion and extension stiffnesses. The results of the first test are shown in figure 6. We see that the mechanism achieves both translation (1-2) and rotation (2-3), as was the original goal. We did, however, notice that the steel sheet metal began to fatigue after repeated testing. At first, it followed the predicted arc about the remote joint center. After several tests though, the stress became increasingly concentrated in a singular point in the center of the sheet metal. This led to a positive feedback cycle where the steel became weaker at that point, leading to increased stress concentrations there, leading to more bending, and so on. This points to a potential future improvement: some sort of cage that forces the sheet metal to retain a circular arc.

In our quantitative analysis of the exoskeleton, we found that it was capable of safely and repeatably providing 7 N of force in both flexion and extension. The device was capable of lifting a 1 kg weight (10 N), but repeated lifts put immense strain on the sheet metal, causing it to warp irreparably. In our qualitative characterization of the stiffness properties of the mechanism, we found that it succeeded in exhibiting high stiffness under both flexion loads and extension loads. Additionally, the stiffness of the exoskeleton in extension was able to be varied by adjusting the tension in the inverse stiffness string. We observed to stable modes: one of high rigidity and the other of moderate compliance.

We interpreted these results to correspond to the friction pad being either engaged or not with the lower link cylinder. When the pad was engaged, the lower link transmitted forces directly to the inverse stiffness spring, making the mechanism as rigid as the spring (which, in the absence of buckling, proved to be fairly rigid). When the pad was not engaged, which corresponded to low tension in the inverse stiffness string, the cylinder was able to rotate with respect to the pad. In this regime, the stiffness of the lower link was determined by the moderate compliance of the bending mode in the primary piece of steel sheet metal.

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