HapLinkage: Prototyping Haptic Proxies for Virtual Hand Tools Using Linkage Mechanism

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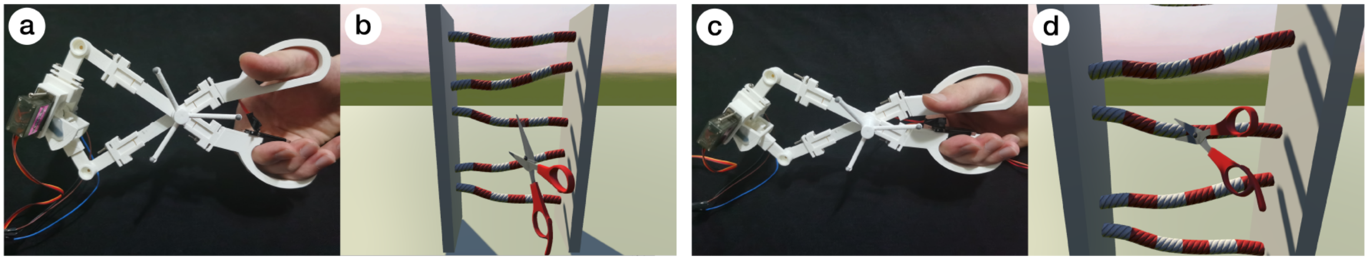

Figure 1. Example prototype of scissors built with HapLinkage, a framework for designing and building haptic proxies for hand tools in VR: It provides different force feedback for (a, b) released and (c, d) actuated states.

ABSTRACT

Haptic simulation of hand tools like wrenches, pliers, scissors and syringes are beneficial for finely detailed skill training in VR, but designing for numerous hand tools usually requires an expert-level knowledge of specific mechanism and protocol. This paper presents HapLinkage, a prototyping framework based on linkage mechanism, that provides typical motion templates and haptic renderers to facilitate proxy design of virtual hand tools. The mechanical structures can be easily modified, for example, to scale the size, or to change the range of motion by selectively changing linkage lengths. Resistant, stop, release, and restoration force feedback are generated by an actuating module as part of the structure. Additional vibration feedback can be generated with a linear actuator. HapLinkage enables easy and quick prototypting of hand tools for diverse VR scenarios, that embody both of their kinetic and haptic properties. Based on interviews with expert designers, it was confirmed that HapLinkage is expressive in designing haptic proxy of hand tools to enhance VR experiences. It also identified potentials and future development of the framework.

Author Keywords

Haptic proxies; prototyping haptic interface; virtual hand tool; linkage mechanism; virtual reality

CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI); Haptic devices;** *Interface design prototyping;*

INTRODUCTION

In recent years, the development of Virtual Reality (VR) technology endows a host of applications in fields like entertainment, gaming, manufacturing, education, skill training, medical operations, etc. It facilities the growth of haptic simulations towards immersive and realistic VR experiences. Interfacing users to VR haptically, it has long understood the need for physical proxy representation of virtual objects [27], i.e., haptic proxy, which takes benefits of enabling users to obtain natural haptic feedback via physically touching, using and manipulating virtual objects. Design concepts like encounter-type haptics [25], haptic retargeting [5], and dynamic passive haptic proxy [42] have been embraced in creating a proxy with reconfigurable properties (i.e., shape, weight, texture, function, location). Physical proxies are often needed in low-fidelity places, and are expected to be easy, cheap, and fast to make, e.g., via 3D printing [42]. In ideal settings, physical proxies can be created ad hoc and modified through the application of various haptic mappings [23].

Existing literature has investigated haptic proxy applications focusing on entertainment and game domains [7, 17, 35], but

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lack simulations of diverse, normal products manipulated by hand in daily life and work. The simulation of such hand tools, including wrenches, pliers, scissors, and syringes, are beneficial for finely detailed skill training in more practical VR scenarios beyond playful experiences [2, 41]. By taking the HP approach, users can have absolute control over the movement and force of the hand tools in VR, and it introduces novel experiences when using the tools under different circumstances. Thus it is necessary to explore diverse scenarios that include the use of numerous hand tools, in the design phase to achieve practical benefits of VR. Unfortunately, designing for diversity in virtual hand tools usually requires expert-level knowledge of specific mechanism and protocol, for kinetic and force rendering alike. This adds barriers for novices, such as designers and makers, in creating new applications that facilitate novel interactions and rich experiences in VR.

This paper presents HapLinkage, a prototyping framework that allows designers to quickly design and build haptic proxies for applications that involve virtual hand tools (Figure 1). It adopts linkage mechanisms that enable rich motions by simple connections of rigid rods [6, 20]. Its essential simplicity and capability of generating rich repetitive motions and managing forces make itself a suitable choice for modeling proxies of hand tools. We derived a design space for virtual hand tools from the collection of 98 existing handheld tools and props. We found that majority of the hand tools involve four motion types (i.e., circular, curved, linear, and complex) and five force profiles (i.e., constant, incremental/decremental, released, restoring, and vibrating). These findings informed the development of HapLinkage.

The HapLinkage framework provides six linkage structure templates for the rapid design of rich kinetic motions. The structure can be easily modified to change a motion range by scaling it or selectively adjusting the parts. In addition to motion design, it provides a variety of haptic feedback by adding an actuating module to the structure. The module drives and restricts the rotation of the structure in response to a user's action for enabling diverse force and tactile feedback. The framework includes a software tool to design the hardware parts including linkage rods, actuating modules, and other subsidiary components. Users can fabricate the designed parts with 3D printing and assemble them to rapidly prototype hand tool proxies for different VR scenarios, such as aforementioned scissors (Figure 1a-d). The demo applications and a subjective user study showed that HapLinkage is easy to use, and expressive in designing haptic proxies of hand tools to explore and enhance VR experiences.

This paper made the following contributions: (1) It presents HapLinkage, a prototyping framework to design and build haptic proxies of virtual hand tools. The framework includes a method to achieve haptic proxies regarding kinetic features (i.e., motions and forces) of hand tools by using linkage mechanisms. (2) It presents usable components including the software tool and hardware modules (the actuating module and subsidiary parts) for the framework. The software tool is built as a plug-in of an existing CAD tool (i.e., FreeCAD) and it provides features to generate 3D models of a physical prototype. The actuating module, which drives the linkage structure in response to users' actions, was designed for easy and rapid prototyping with 3D printing and off-the-shelf electronics. (3) This paper demonstrates various scenario examples of haptic proxy design to show the capability and acceptability of the HapLinkage framework.

RELATED WORK

HapLinkage is inspired by the recent research effort on designing and prototyping haptic proxies to enhance VR experiences. In this section, we first review passive haptic interfaces, actuated haptic proxies, and encountered type haptics. Then we examine the properties of the linkage mechanism and how previous users leverage it in designing interactions.

Haptic Interfaces in VR

Haptic interface plays an important role in creating realistic VR experiences. Researchers have been exploring design and technical solutions to provide haptic feedback in various dimensions (e.g., cutaneous, kinesthetic) and in different ways (e.g., active and passive).

Cutaneous haptic devices stimulate the skin to create contact sensations like indentation and lateral forces, vibration, temperature, and texture [30]. Normally, such tactile stimuli are actively applied on a user's skin, and the tactile devices can more easily be wearable. A good example is finger-based wearable haptic devices, that have been well studied in recent years and shown to be effective in providing localized cutaneous stimuli [23]. Kinesthetic haptic devices, on the other hand, apply forces to guide or inhibit body movement [29]. They display forces or motions through a tool that is usually grounded, to the environment or body. Commonly seen kinethetic haptic devices are presented in forms of manipulandum, grasp, or exoskeleton, which provide forces with multiple-level or on natural Degree of Freedom (DOF) of the body, hand or fingers [29]. For instance, PHANToM [24] is well-known as a grounded haptic display providing force feedback. Grabity [10], Wolverine [11], and Dexmo [15] are recent notable works that simulate grasping interactions and force rendering in VR.

From another perspective, active haptic feedback comprises an actuated end-effector that is normally driven by motors and gears. They are effective in rendering a variety of haptic sensations as many of the cutaneous and kinesthetic devices demonstrated. However, they come at the cost of being complex in mechanical and algorithm design to deliver compelling feedback [16]. In recent years, there is a growing interest in developing passive haptic interfaces, which does not require active actuation. A majority part is a haptic proxy, which is a physical representation of a virtual object. Haptic proxy profits from being low-cost and easy to build, and allows users to obtain natural haptic feedback defined by the proxy's structure and material [42]. Though simple and interesting, the drawback is that the variety of virtual objects and the environment goes much beyond what a single physical proxy can afford.

To tackle the problem, researchers have been exploring design that combines actuation with passive proxy to increase its generality and scalability. This derives several popular research topics, such as reconfigurable proxy, where the shape, structure, weight, or other properties can be manipulated via computer or manually to match the requirement of multiple virtual objects or states. For instance, PuPoP [37] presents a user with changeable shapes to simulate different objects in the user's hand. Shifty [42] and Drag:on [43] allow users to feel various weight distribution of handheld tools. Haptic Resolver [38] and RollingStone [22] enable users to feel finger sliding on various textured surfaces. Another role of the actuated proxy is developing encounter-type haptics [40], or robotic graphics [25], which utilizes robotic arms as actual physical objects to provide haptic feedback [1]. Previous work has developed this idea to present the sense of objects' positions [1], touch [9], and collisions [36]. Meanwhile, The idea has been extended in a variety of ways, e.g., mutual human actuation [8], and iTurk [7].

HapLinkage builds upon the idea of designing and prototyping an actuated passive proxy. Differently, HapLinkage simulates hand tools (e.g., scissors and pliers) via imitating both of their kinetic constrains and haptic sensations. Similar previous works include Haptic Links [35] and VirtualBricks [3], where desired kinematic constrains and haptic sensations (e.g., resistant force) are defined via mechanical joints. HapLinkage is more expressive in terms of simulating hand tools as firstly, linkage mechanism is more akin to many of the hand tools' structure, and secondly, the force is exerted via a motor-driven linkage rod, instead of the joint, which allows rendering both resistant and restoring forces with the same protocol.

Linkage in Interaction Design

HapLinkage adopts linkage mechanisms to facilitate the kinetic movement of hand tools providing haptic feedback. Linkages have been widely utilized for designing movable and transformable tangible objects in interaction design domains. In line with mechanical engineering, several commercial software tools including Linkage [32], LinkageDesigner [13], and SAM [4] enable users to simulate linkage mechanisms. These simulation tools, however, cause difficulties for interaction designers without advanced knowledge of mechanics in dealing with sophisticated and complicated motions of linkage mechanisms. For such designers, several researchers demonstrated interactive systems to design linkage mechanisms with interactive and robust editing [6], placement of extreme locations of parts [26], and sketching desired path [12]. Those systems, adopting computational support, allow designers to obtain mechanism configurations based on the desired movements.

In addition to virtual design tools, several tools link virtual simulation and real-world fabrication of linkage structures. M.Sketch [20] allows designers to draw, simulate, and fabricate arbitrary linkage mechanisms. The tool supports digital fabrication (e.g., laser cutting and 3D printing) of designed linkage parts by exporting vector drawing and 3D models. FoldMecha [28] enables the parametric design of linkage structures that can be fabricated using printed drawings on paper. TrussFormer [21] demonstrates the design and fabrication of large kinetic structures using PET bottles linked by printable hinge parts. Mechanism Perfboard [18] enables designers to iteratively design, build, and test tangible linkage mechanisms through agile workflow on the augmented reality environment. Those tools have advantages of allowing users, especially interaction designers who design, build, and test prototypes of interactive artifacts and systems, to deal with physical structures.

Although linkage mechanisms have significant capabilities of rich kinetic motions, the aforementioned tools in interaction design domains have demonstrated limited applications such as automata, interactive toys, and walking robots. In this research, we focused on utilizing linkage mechanisms to allow interaction designers to effectively design and prototype haptic proxies for VR context. Our framework suggests more practical use of linkage mechanisms that exploits the characteristic of rich kinetic motions derived from simple configurations.

HAPLINKAGE FRAMEWORK

HapLinkage is a prototyping framework to quickly design and build haptic proxies for virtual hand tools using linkage mechanism. We adopted the linkage mechanism and its control method to facilitate the design and prototyping process. Linkage mechanism is capable of generating and editing rich repetitive motions with simply connected rods [6, 20, 31], and it can be simply built with digital fabrication techniques such as 3D printing.

Our framework provides: (1) a set of linkage structure templates for rapid generation of kinetic motions, (2) an actuating module which controls linkage structure for managing variety of haptic profiles, and (3) a software tool integrated with an existing CAD tool for designing and customizing motions. We focused on hand tools that have potential benefits for practical VR scenarios, such as skill training and remote working, in line with previous virtual hand tool studies [2, 19, 34, 41]. This section illustrates the design space and implementation of our framework for motion types and force profiles through exploring kinetic properties of a variety of hand tools.

Design Space of Virtual Hand Tools

To bring existing hand tools to VR scenarios, understanding their kinetic properties was essential. We firstly collected various tools and props that can be powered by human hand; We extended the scope of 'hand tool' beyond a specific means of crafts and carpentry. From the literature [14, 33, 39], e-commerce platforms (e.g., Amazon), and inspirational image sources (e.g., Pinterest and Instagram), 98 types of products, which can be manipulated by hand along a certain axis, were collected (excluding duplicated types). The collected items were categorized according to their kinetic features by affinity diagramming. We derived two meaningful attributes of hand tools: motion types and force profiles, as shown in Figure 2.

Motion Types

We derived four major motion types of hand tools regarding the position of a grasping hand. ***Circular*** type shows an infinite rotary motion driven by a crank or key handle. Examples of this type include hand blenders, bench vices, and coffee grinders that are commonly used to mix, fasten, and grind materials by repetitive manipulation. ***Curved*** type shows a repetitive motion of a portion of the circular motion. The

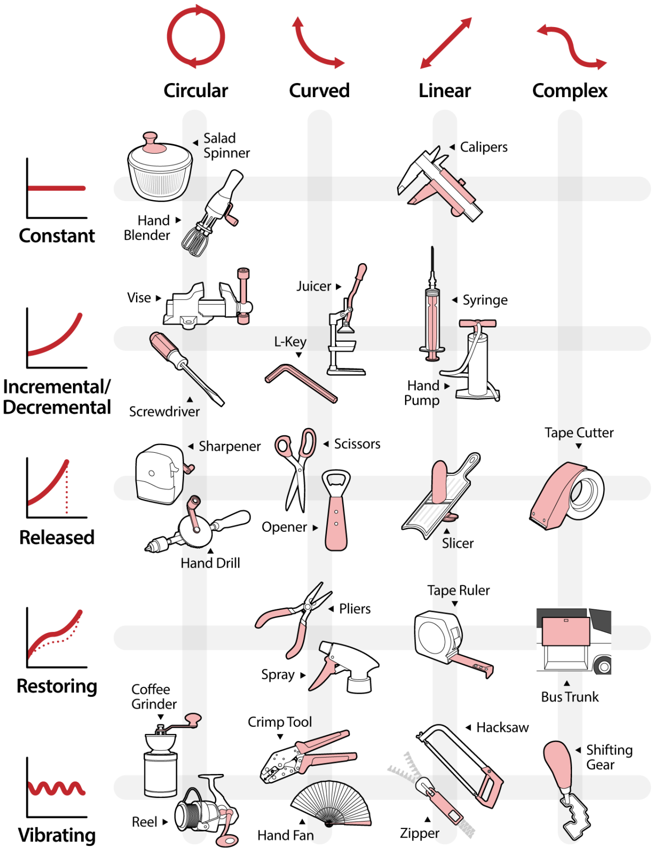


Figure 2. A design space of virtual hand tools derived from 98 types of existing tools and props. It includes four motions types and five force profiles as kinetic characteristics.

tools consisting of lever-mechanism, such as pliers, scissors, juicers, can be included in this type. They are often used to grasp and squeeze certain materials and some of them have restoration force to facilitate repetitive actions. ***Linear*** type shows straight motion and frequently appeared from the tools consisting of sliding mechanism (e.g., shell and rails). This type includes the tools that measure, compress, open and close materials: calipers, syringes, and zippers. Few tools, such as knives and hacksaws, which cut or scrape materials on the straight direction can also be included in the linear type. Meanwhile, several hand tools, such as gearshift and tape cutter, have distinct motions compared to the aforementioned types; ***Complex*** type shows motions consisting of two or more directions and irregular curves (e.g., L-shape and S-shape).

Except for several tools which are not hinged (e.g., spoon), we identified that the four motion types, including repetitive movements, can be derived from simple four-bar and six-bar linkage mechanisms [31]. Based on these motion types, we attempted to adopt a top-down design approach to our framework as similar to previous studies [6, 18]. We designed linkage structure templates that allow users to select the desired motion first and tune the kinetic properties later.

Force Profiles

Besides motions, we derived distinctive force profiles related to possible haptic proxies from the collected hand tools. Hand tools are usually used to conduct a certain task for working with materials so they can provide different sensations according to their structure and associate materials. Below we describe five types of haptic profiles.

Constant: Some tools do not include a clear variation of force while manipulating. This can appear in scenarios that do not involve explicit material processing. Tools of these kind can be used for mixing and measuring something instead of cutting and squeezing it (e.g., salad spinners and hand blenders). They are often constrained as a guided motion by rails (e.g., calipers and shifting gears).

Incremental/Decremental: Typical hand tools, which are used to squeeze or fasten materials, can include this profile (e.g., press juicers and syringes). Because of elasticity or viscosity of target materials, a continuous action brings the increase of reacted force–eventually stops at a certain point. Reversely, users feel decremental forces when using tools to loosen materials.

Released: Several tools have a clear endpoint associated with job completion, such as cutting and drilling (e.g., scissors and manual hand drills). They may involve the increase of force and lose the action force at a certain moment. Their use is irreversible and the target materials should be unrecoverable.

Restoring: Restoring device such as spring is often equipped to hand tools for efficient use of repetitive actions (e.g., sprays and pliers). When a user relaxes his or her hand, the tool begins to return its original position for the next action.

Vibrating: Vibration, a distinct sensation, is sometimes carried by physical characteristics of hand tools. For instance, coffee grinder and hacksaw include vibrating feedback due to their toothed blades. Other tools including special mechanisms for locking steps (e.g., hand fan, clamps, and zippers) include clicking feedback according to the amount of travel.

The aforementioned profiles are highly related to characteristics of tools themselves but sensations including *stop* and *vibration* can also be caused by the target materials (e.g., different sizes and textures bring distinct sensations). We explored several techniques to control linkage structures to provide such force and tactile profiles. Details of how to derive the motion and haptic proxies of virtual hand tools will be described in the next section.

Motion Design with Linkages

HapLinkage framework adopts template-based design to create a prototype for haptic proxies. It provides a set of linkage structure templates that generate the identified motion types (i.e., circular, curved, linear, and complex). Users can focus on selecting a motion, which is similar to their desired one, from the templates instead of constructing a structure from scratch. They can then have a fine-tuning process to define the range and size of motion according to the hand tool which will be simulated. The designed linkage parts can be 3D-printed and assembled. Our framework also includes several subsidiary parts that make the created linkage be manipulated as similar to existing hand tools.

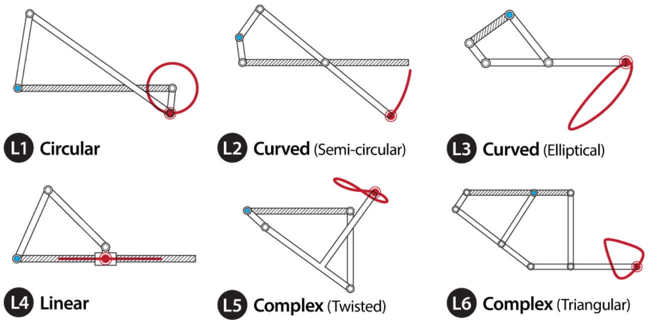


Figure 3. Linkage structure templates generating diverse motions for the four motion types (circular, curved, linear, and complex). Blue-colored joints are recommended positions to equip the actuating module which controls the associated linkage rods. The red paths represent relative motions to the shaded linkage rods held by a hand or grounded.

Linkage Structure Templates

To derive motions for hand tools, we explored existing linkage structures including four-bar and six-bar linkages. They are basic and popular configurations of linkage structure capable of generating diverse rotary and repetitive motions by using a simple connection of four or six rods [18]. A typical linkage consists of several grounded cranks and couplers connecting them. We varied the topology of four-bar and six-bar linkages to obtain each of the motion types, and chose each target point where users actually grasp and manipulate (Figure 3).

Circular motion can be simply generated by a template including a shorter crank that entirely rotates (L1). *Curved* motion can be created by two templates: semi-circular (L2) and elliptical (L3) ones. The semi-circular template enables arced motion by an extended crank. It produces a repetitive motion on the circular sector as similar to typical hinged hand tools, such as scissors and pliers. Meanwhile, elliptical motion can be obtained by a trajectory of an extended point on a coupler. This template can be used when users require more gradual curves comparing to the semi-circular template that requires much longer rods. *Linear* motion can be produced by substitution of a crank to a slider (L4). Although typical four-bar linkage has the capability of creating a section of linear motion, this structure template can provide more stable and precise control of linear motion.

Complex motion, e.g., distinct motions including S- and L-shape, can be created by two linkage structure templates: twisted (L5) and triangular (L6) ones. The twisting motion can be obtained by a configuration of four-bar linkage (different topology of elliptical one). Different shape of the coupler brings an intersection point on trajectory. The triangular motion is derived from the six-bar Stephenson III linkage. This motion includes three vertices of a sudden change of entry angle so the partial adoption can be used to create a L-shape motion. Users can choose from the templates to get an appropriate motion for designing a hand tool prototype.

Scale and Range of Motion

Although the templates can cover the diverse motions of hand tools, it is essential to modify detailed motions to match to existing tools. The scale and range of motion should be determined according to the type of target tool. For instance, a syringe and hand pump have different travel range while sharing the same motion due to their scale difference. Pliers and scissors also have different angle range because of their purpose. To obtain diverse motions for numerous hand tools, we adopted a parametric design technique that can generate alternative motions of a linkage configuration by adjusting of length of each rod [6, 18, 28].

Our framework includes three strategies to adjust the range and scale of motions (Figure 4). First, *scaling the entire structure* is to increase or decrease all the rods of the structure by a constant ratio. It facilitates simple and intuitive adjustments while keeping the shape of motion. Second, *adjusting an individual rod* is an action to change the length of a specific rod to change the motion path. For instance, a change of a point on a grounded crank increases the radius of motion. However, it often affects the shape of the motion path if a target rod is not hinged to ground. Third, *restricting motion angle* is constraining a linkage rod to rotate with a limited angle range. This is not enabled by the linkage structure but carried by our actuating module, which will be illustrated in the haptic proxies section.

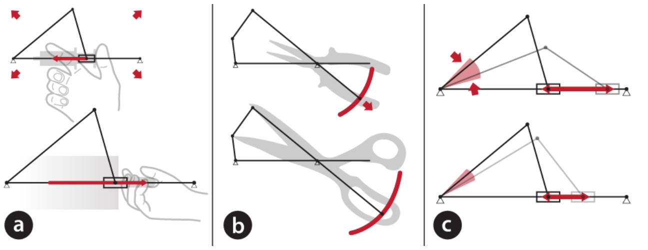


Figure 4. Three strategies to adjust range and scale of motions for obtaining diverse motions: (a) scaling the entire structure, (b) adjusting an individual rod, and (c) restricting motion angle.

Linkage Rods and Subsidiary Components

After designing the motion of the linkage structure, the mechanism can be 3D-printed and assembled for building a prototype of virtual hand tools. We designed a schematic 3D model of a linkage rod including a *snap-fit joint* and *tunable mechanism*. The customized snap-fit joint is equipped to each end of linkage rods to enable easy and rapid assembly (Figure 5a). It also provides more stable actuating with less distortion and loosening comparing to a bolted joint.

The tunable mechanism was equipped in the middle of a linkage rod for fine-tuning of its length (Figure 5b). Because several physical aspects including friction, distortion, and tolerance of linkage parts affect the motion, it is necessary to conduct trials and errors for prototyping [20]. To reduce the repetitive printing and assembling process, we designed a sliding mechanism, which can be assembled with two machine screws. It enables slight adjustment of the length of a linkage rod with tightening or loosening the screws like a conventional screw-drive mechanism.

We also designed several subsidiary components to allow users to manipulate the created linkage structures as typical hand tools. First, a variety of *hand grips*, which are directly held by users, were designed to be connected to the linkage rods. We explored existing hand grips including diagonal, crank, trigger,

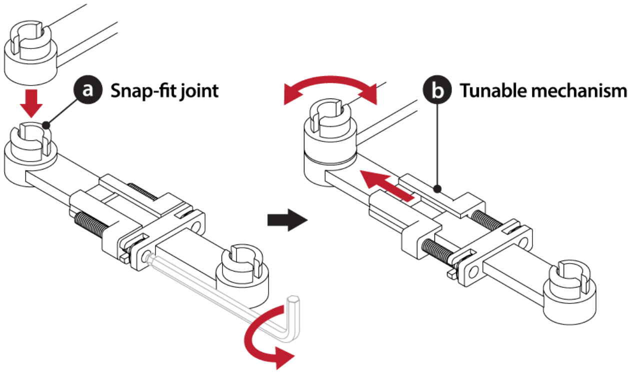


Figure 5. A linkage rod includes (a) snap-fit joint and (b) tunable mechanism for effective assembling and tuning process.

lever, finger types, and modeled each type as examples given with the mechanism structure templates (Figure 6a). The grips can be located on the associated linkage rod having the target point of motion path and it enables similar usage behavior to existing hand tools.

The second subsidiary component is *base*, a structure to fix the linkage mechanism to the ground (Figure 6b). Some hand tools are used when they are laid on the floor or desk and grasped by one hand (e.g., paper trimmer and coffee grinder). The base components, which have a similar shape and dimension of the original tool, can be built and connected to the linkage structure to provide the same usage behaviors. The base can be simply connected with a linkage rod by inserting the rod to its groove.

Last, *docking joint* and *dummy grip* are used for simulating several hand tools that are not fully fixed, such as knives and hacksaws. They often allow flexible movement at a certain point as well as free movement in the air. For instance, knives can have a linear motion to cut a paper but its angle can be varied by the user. It can also be detached from the ground after cutting. To support such behaviors, we designed two docking joints, connectable to a dummy grip, based on a sphere- and cylinder-joint mechanism (Figure 6c, d), respectively. It replaces the aforementioned hand grip part and allows users to flexibly attach, detach, and move the dummy grip to manipulate the linkage mechanism.

Providing Haptic Proxies

A linkage structure itself is a means for a mechanical movement that is capable to deliver forces to the end-effector such as grips on users' hands. HapLinkage framework uses an actuating module, which can be attached to one of the joints, to render forces according to users' manipulation. We designed the actuating module that can drive or restrict motions of the assembled linkage structure to emulate the five representative haptic profiles (constant, incremental/decremental, released, restoring, and vibrating ones).

Actuating Module Design

We designed a simple actuating module to support the prototyping of virtual hand tools. The basic mechanism is to manage the rotation of a single linkage rod by docking the motor and sensor. To provide similar haptic profiles to typical hand tools, it was necessary to limit, drive, restore the movement of linkage structure simultaneously according to users' manipulation. We attempted to adopt a simple method to push a linkage rod bidirectionally regarding the current position by using a single servo motor. The module was designed to be 3D-printed and can be simply attached to a linkage rod parts.

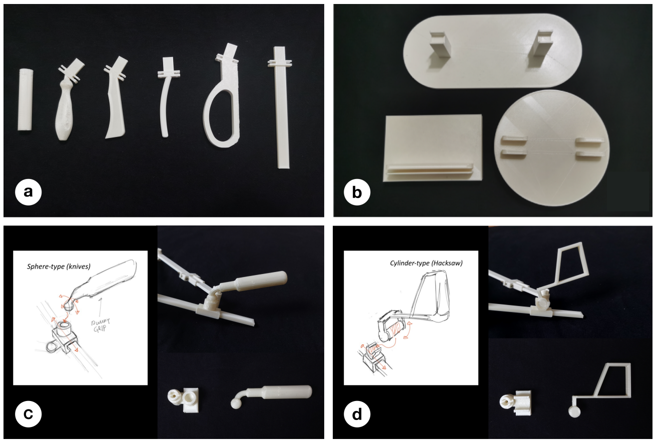


Figure 6. Examples of subsidiary components: (a) hand grips, (b) bases, and (c, d) docking joints and dummy grips. They can be added to the created linkage structure to provide similar experiences to hand tools.

The module consists of two major parts: *support frame* and *cage* (Figure 7a and b, respectively). The support frame is a structure holding an encoder (Figure 7c) and a servo motor (Figure 7d) which drives the cage. The fan-shaped cage, connected to the servo motor, has two bars at each side to push the driving linkage rod (Figure 7e) in both directions. The support frame is attached to the base linkage rod (Figure 7f) and the cage can control the relative angle between the driving and base linkage rods. In addition to the hard bars, the cage has two holes for equipping rubber bands (Figure 7e) that can enable various levels of restoration forces.

The cage structure can render haptic feedback, such as resisting, stopping, and restoring the movement of linkage structure, by delicate control of its rotation according to the current angle between two associated linkage bars. The encoder (GT-B) read the angle at a resolution of 0.022° and the value is then used to control the next rotary position of the cage. The opening angle of the moving cage can be varied based on the mechanism and its application. For instance, the shape can be decided according to the minimum and maximum angle between the two linkages (base and driving ones) as well as the necessity of quick responses for the application context. Through the empirical design, we set the default opening angle that limits the driving linkage in 60° range. We used compact-sized MG90D servo motor (capable to provide a torque of 2.1kg/cm) to minimize the weight of hardware parts.

Based on our linkage structure templates, we decided key joints (blue-colored joints in Figure 3) as a recommended position to equip the actuating module. The key joints were chosen to control the entire structure with minimal change of angle with less physical interruption; The rationale was that each key joint between two linkage rods has (1) enough space for additional parts of the actuating module and (2) potential to affect large movement on hand-grip position with small change by the module.

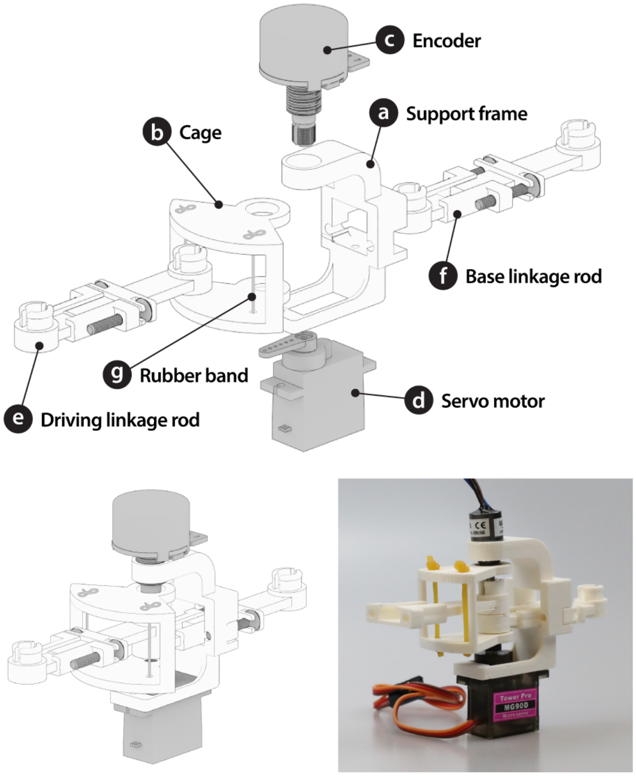


Figure 7. Design of the actuating module composed of (a) support frame and (b) moving cage. The support frame equips (c) encoder and (d) servo motor to control angle between (f) driving and (e) base linkage rods. (g) Rubber bands can be added when restoration force is needed.

Controlling Force and Tactile Profiles

To demonstrate the capabilities of haptic rendering with the proposed structure and actuating module, we designed and implemented the method for rendering diverse force profiles by driving and restricting linkage structure. Here we illustrate how the actuating module realizes diverse force profiles.

Resistant force is one of the typical force elements that users can feel in using hand tools. The force, which is applied in response to users' input actions, is useful in representing friction or loaded weight of the tool. The perception of resistant force helps one differentiate among tools and target materials. Using the actuating module, such resistance can be rendered by hindering the driving linkage rod's actuation (Figure 8a). When a user operates the linkage structure, the module runs the motor at the same traveling value read from the encoder. The continuous control at every frame can achieve that the cage hinders the expected movement of the driving rod at the next frame due to the motor's torque, as shown in Figure 8d. Here, the different traveling speeds of the motor can vary the resistant force and obtain ***constant***, ***incremental***, and ***decremental*** force profiles.

In our design space, the increase of reaction forces brings ***stop*** at a certain point (Figure 8e). This is also useful in emulating various scenarios where the tool is used on hard materials, such as metal or walnut. This sensation can easily be rendered by placing and fixing the cage of the actuating module at a certain angular position to stop. On the contrary, the ***released*** sensation can be created by suddenly disengaging the cage that gives users the perception of losing the resistance force (Figure 8e).

```
Stop & Release Loop :
    If $EncoderAngle > Threshold$ then
        WriteServo($Threshold - HalfOfCageAngle$)
    Else
        WriteServo($MotorAngle$)
```

Restoration involves a force that tends to bring the structure back toward its original setting of position, angle, or shape. The force is exerted in a direction to oppose the deformation. A mechanical way to render such restoration force is challenging because it often requires sophisticated motor control with high precision. The restoring force could be easily achieved by rotating the cage against the user's hand movement. Here to implement a more convincing ***restoring*** profile, we used the rubber bands (Figure 8b) along with rotating the module to render the restoration force in an easy and intuitive way. The rubber band is very common in our life, and it is easy to control the deformation degree of rubber band by adjusting the position difference between the driving linkage rod and cage. The rubber is stretched tightly by default and moved to just get in touch with the driving linkage rod. When the user operates the linkage mechanism, the driving linkage rod passively moves and deforms the rubber band. At that moment, the actuation module actively rotates the cage in response to the rotation of the rod to adjust the force (Figure 8f). The elaborate control of the rubber band's deformation could generate various levels of the restoration force. The maximum force is generated when the rubber band reaches bars at the cage's edges. Below is an example of single way resistance and restoration control (e.g., pliers).

```
Resistant & Restoration Force Loop :
    If $EncoderAngle > MotorAngle$ then
        $MotorAngle = MotorAngle + ResistanceFactor$
    Else $EncoderAngle < MotorAngle$ then
        $MotorAngle = MotorAngle - RestorationFactor$
    Update $ResistanceFactor, RestorationFactor$
    WriteServo($MotorAngle - HalfOfCageAngle$)
```

Aside from the previously described sensations, vibration is often carried with distinct mechanisms and materials of original hand tools. As we illustrated in the design space section, toothed blades of several tools can generate vibrations. In addition, vibrations or vibrotactile feedback can also be caused by the target materials of tools (e.g., paper or corrugated cardboard). Due to the limitation of the motor speed, it was challenging to implement a ***vibrating*** profile with our actuating module. We adopted a high-frequency linear actuator (Apple Taptic Engine) as an additional module, which can be attached to the hand-grips of prototypes (Figure 8c). The vibration module produces vibrotactile feedback from the inputs (audio signals), made by various sounds from original tools.

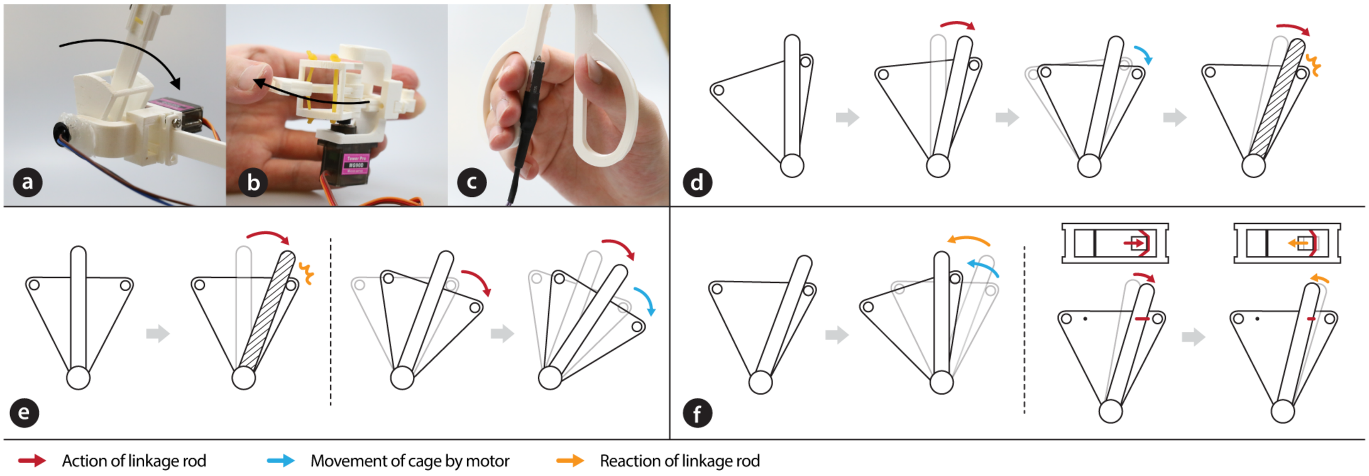


Figure 8. HapLinkage renders haptic proxies by using (a, b) the actuation module and (c) linear actuator: It provides (d) resistant force which hinders the expected actuation, (e) stop and release, and (f) restoration force to push back to the original position.

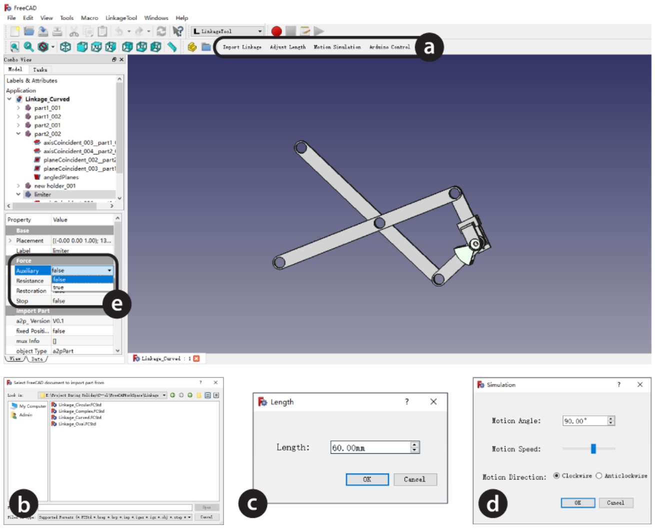
PROTOTYPING WITH HAPLINKAGE

This section illustrates the flow of prototyping using the HapLinkage framework. Our framework provides a software tool and various models for fabricating physical prototypes of virtual hand tools. The software for designing Linkage structure was implemented as a plug-in of an existing CAD tool, FreeCAD. 3D models including hand-grips and bases can be fabricated with typical 3D printers.

Design: When the plug-in of FreeCAD is activated, it shows the menus for designing the linkage structure (Figure 9a). users can import one of the templates from the list using the import menu (Figure 9b). The imported structure can be freely navigated on the 3D space. To adjust the length of a linkage rod, users can select one and click the ‘adjust length’ menu and put the length value to the popup dialog (Figure 9c). Then the software calculates the topology of the linkage mechanism for the new length. The software also enables visual simulation that shows how the mechanism actuates according to a certain range of rotation (Figure 9d). When users select the part of the actuating module on the space, the property tab of FreeCAD shows the items for force profiles (Figure 9e). Users can activate or deactivate each profile according to their needs for further programming phase.

Build: After design and simulation, the software provides the parts for linkage rods that include snap-fit joints and tunable mechanisms. Users can fabricate all the required parts (the linkage rods, subsidiary components, and actuating modules) and assemble while referring to the visualization of the software. At this phase, users add the servo motor and encoder to the actuating module.

Test: According to the setting of force profile on the property tab, the system provides base codes for Arduino, which controls the actuating and vibration modules. Users upload the code with inputting variables (e.g., the motor’s traveling speed) and connect electronic parts to Arduino. Then users can test the prototype and check that it can provide a similar sensation to the original hand tool. At this phase, the prototype can equip markers for VR and connected to VR application software for immersive testing.



Property	Value
Base	
Placement	[(-0.00 0.00 1.00); 13...
Label	limiter
Force	
Auxiliary	false
Resistance	false
Restoration	true
Stop	false
Import Part	
a2p_Version	V0.1
fixed Positi...	false
mux Info	[]
object Type	a2pPart

Length: 60.00mm

Motion Angle: 90.00°

Motion Speed:

Motion Direction: ● Clockwise ○ Anticlockwise

Figure 9. Snapshot of the software tool integrated with FreeCAD: It provides (a) menus for (b) importing linkage structure templates, (c) adjusting linkage length, and (d) simulating motion. (e) Force profiles can be selected by property tab.

Modify: If the prototype needs to be modified, users can iteratively edit the Arduino code and tune the lengths of linkage rods with the tunable mechanisms. Users can also redesign and fabricate the parts if there are critical problems such as physical mismatches and interruptions.

APPLICATIONS

With HapLinakge, designers can quickly design and prototype a rich set of haptic proxies which afford diverse kinetic and haptic properties. We present several virtual hand tools that were designed and implemented based on the framework.

Coffee Grinder: With a manual coffee grinder, a user rotates the handle clockwise or counterclockwise (Figure 10a). Grinding coffee beans generates constant friction while vibrations

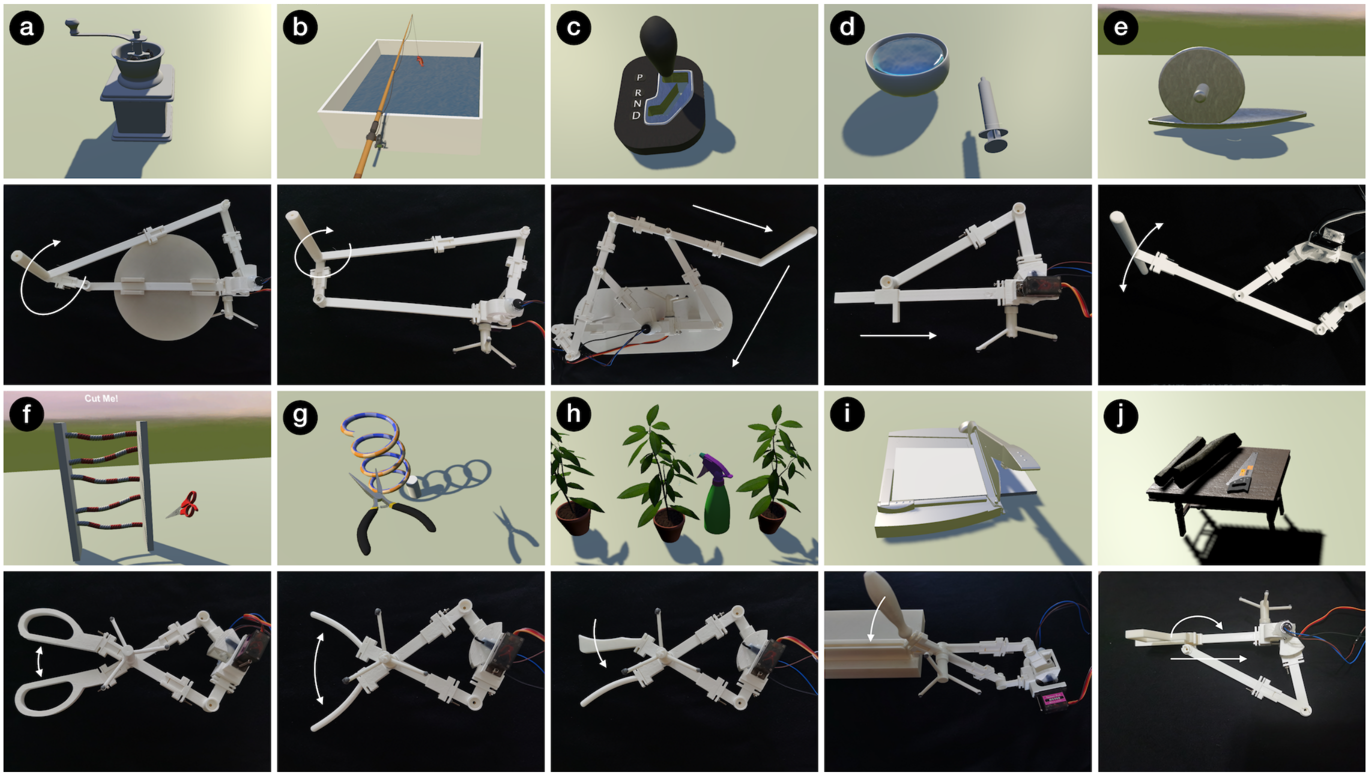


Figure 10. Demo applications for (a) coffee grinder, (b) fishing, (c) stick shift, (d) injector, (e) medicine roller, (f) scissors, (g) spring pliers, (h) spray bottle, (i) paper trimmer, and (j) saw.

will also be felt. As a result, we used the *Circular* structure, let the actuating module generates a constant resistance force, and the linear actuator rendered vibrations. As the grinder is usually placed on a table, this demo prototype was docked to the base such that the force rendering got grounded.

Fishing: This application allows the user to rotate the roller of the fishing rod to retract or release the line (Figure 10b). We used the *Circular* structure to simulate the rotation of the roller. *Restoration Force* and *Vibration* are used to simulate fish hooking. Actuation of the motor can make users easily release the line. The user can adjust the radius of the rotating circle and use one hand to hold it, another hand to rotate.

Stick Shift: This application allows user to shift a virtual gear while playing VR racing games. The gear stick moves along a specific path, stops at each level, and the user has to push harder to overcome the resistance to move to the next gear levels (Figure 10c). *Complex (triangular)* structure was used to simulate a two-level gear shift interface, where the user first pushes the stick downwards, restricted at the end by a stop force. The user then moves the stick leftwards to shift the gear.

Injector: This application enables the user to push syringe injection (Figure 10d). The user pushes the injection rod to extrude the liquid in the injection tube. We used the *Linear* structure to implement the pull mechanism and contact cube is added to the structure to facilitate user push. *Restoration Force* is provided to simulate the resistance of liquids. The user can adjust the moving distance of the injector and hold it in one hand. With the gradual promotion, users can feel less and less force.

Medicine Roller: The Chinese Medicine Roller is an old tradition to crush herbs. Users push and pull the roller handle along the groove, which moves back and forth in a curved path (Figure 10e). The *Curve* template was used to build a medicine roller proxy, and a customized handle was attached for bimanual operation. As the force was grounded, we fixed the structure to a stand. The proxy rendered constant resistant force, as well as vibrations when users operate with the roller.

Scissors: This application simulates scissors and allows the user to cut paper with it (Figure 10f). We used the *Semi-circular* structure to simulate the opening and closing of scissors and two handles are printed for grasp. When the user starts to cut paper, the slight *Restoration Force* is provided and the *Vibration* makes the paper-cut collision more realistic. The maximum opening angle of the scissor can be easily changed by adjusting the length of the key linkage bar.

Spring Pliers: This application allows the user to use the pliers to clip wire (Figure 10g). *Restoring* force was added such that users feel elastic force between the hand grips. Adding no forces by hands, the pliers will return to its original shape. We tuned the actuating module's motion with the rubber bands, to generate a strong restoring force.

Spray Bottle: We developed a proxy for hand pressure sprinkling can, the structure of which was similar to a scissor, but we changed the handle to support users to grab in a different way (Figure 10h). This was an interesting attempt, as we noticed that although the styles of the two are very different, their inherent motion structures could be represented in almost the same way. Very different was the haptic rendering profiles, wherewith this example, *Restoring* force was used, and the handle always returned to its original position.

Paper Trimmer: Compared with the scissors, a trimmer is of larger size, run with a single hand, and grounded. We used a similar structure with the scissor example but docked one linkage bar onto the table (Figure 10i). We also modified the handle such that users could operate with it like using a trimmer. The force rendering method with the trimmer was much alike the one with the scissor. In this example, a user can cut a large piece of paper sheet with a straight edge.

Saw: A saw was demonstrated, in a scene of cutting a wooden stake (Figure 10j). Unlike the other examples, this one used the docking joint approach. The handheld part was simply a dummy grip, and it only worked when attached to the base and formed a linkage structure of linear motion. To simplify the vibration rendering, the cylinder-joint was designed and printed with textured surfaces (i.e., bumps).

EXPERT INTERVIEW

We conducted an expert interview through online as an initial step to evaluate HapLinkage. The purpose of the interview was to gather feedback and suggestions from expert designers in the VR domain.

Participants: Three expert designers (1 female, avg. age = 27.3) were invited who had rich experiences in VR game design, tangible interaction design, and HCI research, respectively. One of them is from a company and the other two are from universities. None of them had conducted projects similar to this, but they were familiar with the concepts of physical proxies and haptic interfaces. One of them learned mechanical design during her undergraduate study. Each participant was rewarded with around $USD20 for their participation.

Procedure: Each of the designers was interviewed online. They were first shown the slides and demo videos that explained the project, including the concept of the prototyping framework and its features, design and fabricate process, and more importantly, demo scenarios. We then had an open-ended yet in-depth discussion, mainly to collect their thoughts about HapLinkage, and any potential suggestions for improvement. The interview lasted on average 40 mins per participant.

Result: All the designers were interested in the topic of the project and agreed that HapLinkage could potentially ease the design process and enrich user experiences in the VR. They agreed with many advantages that we presented in the paper and the video. On the other hand, HapLinakge is a prototyping framework for low-fidelity prototypes. It raised several concerns that were shared by the designers. There still exists some gap between the physical representation and the target object. For instance, the demo applications showed the prototypes not exactly of the same size as the targets. Meanwhile, building the prototypes need to consider the rest parts on the target objects, e.g., to consider how to represent the body of the grinder besides the kinetic part. Designers were also concerned about the durability of the parts, repeated rotation may cause wear to the joints.

It can be seen that HapLinakge proposed some structure templates that had a certain generalization ability. However, it might be a bottleneck for HapLinkage and other projects of the same kind, that we aimed to imitate the inherent structures of the handtools, instead of reaching solutions via innovation in the means of realization. For instance, it is not sure whether people could come up with a novel design beyond the presented ones. On the other hand, the current approach was intuitive and easy to understand, so it could be more easily adopted by designers. Saying that the learning curve still exists. People who lack mechanical design knowledge would have difficulty in understanding the structures, and mastering the customization based on the templates could be not easy. This also proposed a new requirement to improve the software tool, which could be more capable to guide the users, in a step by step way.

DISCUSSION AND FUTURE WORK

Based on our design and application demonstrations of the HapLinkage framework, we identified several issues and potential future works to discuss the prototyping of haptic proxies.

Rapid Prototyping versus Reliable Simulation

HapLinkage is a prototyping framework for designers to explore various VR scenarios related to hand tools. Since prototyping haptic experiences is challenging for people without a strong technical background, we focus our current work on providing designers an easy and rapid way to explore and test their ideas in early design phases. Thus, it adopted simple structure templates and light electronic parts (an encoder and servo motor) for fabricating and assembling process. Based on the demonstrations and feedback, we found that our approach is feasible to design and implement haptic proxies as low-fidelity prototypes.

In low-fidelity prototyping, templates allow designers to rapidly create the structure with simple selections and minimum modification. However, experts concerned its limitation in generalized design. Simple hardware parts with minimum subsidiary components support rapid design but it might fail to reflect the tactile sensations–the shape and volume of grips or bodies. We developed the software tool as a plug-in of the existing CAD system but it could not support the smooth integration with free modeling. It is necessary to include flexible workflow and functions where designers can choose the appropriate fidelity and task load according to their needs.

Note that the simplicity in design and configuring actuating module comes with a trade-off that the range of resistance and restoration force is pretty much restrained by the structure and performance of the actuating module (e.g., the sensitivity of the encoder and speed of the motor). Another shortcoming is a HapLinkage structure can either render a passive resistant force without the rubber band, or the spring force with the rubber band, but not both. The current module design has the advantage to allow the use of off-the-shelf parts, but future research will look into improvements in reliability in generated haptic output. Reflecting on a wide range of fidelity for prototyping, further studies could investigate designers' needs and discuss the trade-off between rapidity and reliability of prototypes for haptic proxy design.

Using Linkage Mechanisms for Prototyping Hand Tools

In this work, we demonstrated the feasibility of using linkage mechanisms as a medium for prototyping haptic proxies that can generate and control different motions and force profiles. Since our demonstration is limited to a relatively small number of virtual hand tool scenarios, we see it an important next step to investigate linkage mechanisms in broader, practical scenarios. Our current investigation does not cover large objects used by both hands, such as garden shears and water pump pliers. The servo motors used in our current implementation may be insufficient to generate enough forces for scenarios using both hands. Moreover, the printed parts especially the longer ones could be bent, causing distortions and inaccuracy in movement. We will, thus, explore alternative design solutions (e.g., stronger rods with a layered structure) using simulation software.

Most hand tools, which can be covered by HapLinkage, should include a clear mechanical structure and point of action. However, tools in real-world scenarios may involve free-form motion or entirely released state. In our current implementation, the linked parts have restricted movement and slight frictions among moving parts even though the actuating module is turned off. To resolve this, we provided the docking mechanism (the docking joint and dummy grip) for supporting such hand tools that are not fully fixed (e.g., knives and hacksaws). However, there still exist numerous hand tools and props that could not be covered by our framework. For example, spoons, paddles, and chopsticks for shacking and stirring materials could not be implemented with our framework. Moreover, some props such as water faucet requires the serial composition of multiple mechanism units. Future work could investigate a way to emulate such flexible and complex hand tools and props using linkage mechanisms.

Impact of Haptic Proxy Design with HapLinkage

For the HapLinkage framework, we focused on hand tools while expecting the potential and practical benefits of VR application, such as education and skill training. We identified that our demonstration could successfully emulate specific tasks while using associated tools. However, this study has a limitation that it did not evaluate the approach with structured user studies. Future work can conduct quantitative and qualitative studies to identify the impact and applicability of prototyping haptic proxies with linkage mechanisms. Observations of prototyping sessions with practitioners (designers and developers in AR domains) could reveal the needs and impact of haptic proxy design regarding creating novel applications for virtual hand tools. Beyond the VR domain, we see that our framework can be used in the design of smart hand tool [44]. We also see the potential of it in augmenting the existing hand tools for new applications, such as prohibiting the use of certain tools for safety sake. Moreover, further explorations for diverse application domains, including entertainment and accessibility, could be conducted.

Improvement of Prototyping System

Further development of software tools could include more templates for hand-grips and bases for providing a natural experience. It is also important to extend the system to support customization. The design of hardware parts (e.g., the tunable mechanism) could be improved as a modular kit for reusable prototyping. In addition, the development process of an actual VR application could also be integrated with the prototyping. For example, the design software can indicate the position of a joint where a tracking marker is attachable. Besides the tuning on motion features, allowing users to create and customize haptic events is also desired. Further implementation of the protocol could enable the smooth connection between environments of physical computing (e.g., Arudino) and VR application (e.g., Unity) for integrated development and testing process.

CONCLUSION

In this paper, we presented a prototyping framework for haptic proxy design by using linkage mechanisms. Based on the derived design space, it was designed to support for designing, building, and controlling the motions and forces of linkage mechanisms by hardware parts and an actuating module. We demonstrated exemplary VR scenarios for virtual hand tools, created by the HapLinkage framework. We expect that our framework and demonstrations will benefit haptic proxy design and prototyping haptic interfaces for providing better and more diverse VR experiences.

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