Toward Handling the Complexities of Non-Anthropomorphic Hands

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Figure 1: Non-anthropomorphic hands exist in both virtual and physical reality.

ABSTRACT

Virtual reality allows us to operate bodies that differ substantially from our own. However, avatars with different topologies than the human form require control schemes and interfaces that effectively translate between user and avatar. In this position paper, we discuss the concept of "non-anthropomorphic designs" that are inhuman in not just appearance, but in topology and/or motion. We examine current implementations of real and virtual non-anthropomorphic hands (NAHs), finding that existing NAHs generally rely on one-to-one or reductionist control strategies that limit their possible forms. We discuss the structure of a functional NAH system and design considerations for each component, including metrics for evaluating NAH system performance. The terminology and design considerations presented here support future research on NAHs in virtual and physical reality, as well as virtual and physical tool design, the body schema, and novel control interfaces and mappings.

CCS CONCEPTS

• **Human-centered computing** → **Interaction design theory, concepts and paradigms**; Human computer interaction (HCI); • **Applied computing**; • **General and reference**;

KEYWORDS

virtual reality, non-anthropomorphic avatars, body schema, homologous limbs, non-homologous limbs, non-homologous avatars

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1 INTRODUCTION

Up until the advent of virtual reality, people augmented their bodies with the objects they wore and the tools they used [37]. These augmentations had both cognitive and physical effects; however, all objects and tools were constrained by the limitations of their materials and mechanics. Virtual reality (VR) transcends those limitations, allowing novel representations of our bodies (i.e. avatars) that support a new exploration of our relationship to bodies, tools, and the sense of self [29]. However, prior explorations of non-human-shaped (i.e. non-anthropomorphic) virtual representations have, with few exceptions [46, 76, 82], focused heavily on homologous forms—those forms with structure-preserving mappings between real limbs and the virtual avatar. For example, in VR, a person might become a robot or an animal with four limbs, but transformation into an animal such as the eight-limbed lobster described by Jaron Lanier in the early days of VR [49] is highly uncommon. An extremely challenging hypothetical avatar that illustrates the limitations of homologous mappings is that of the octopus—how would a human control and embody a virtual cephalopod? We need a method for generating and refining control schemes that do not rely on homologous mappings if we are to access all the forms of experience that VR has to offer.

In this position paper, we propose a concept for structuring and evaluating such non-homologous avatars, with a specific focus on the challenge of non-anthropomorphic hands (NAHs), such as the examples shown in Figure 1. We first present a survey of existing literature on NAHs in both physical and virtual reality. We use this

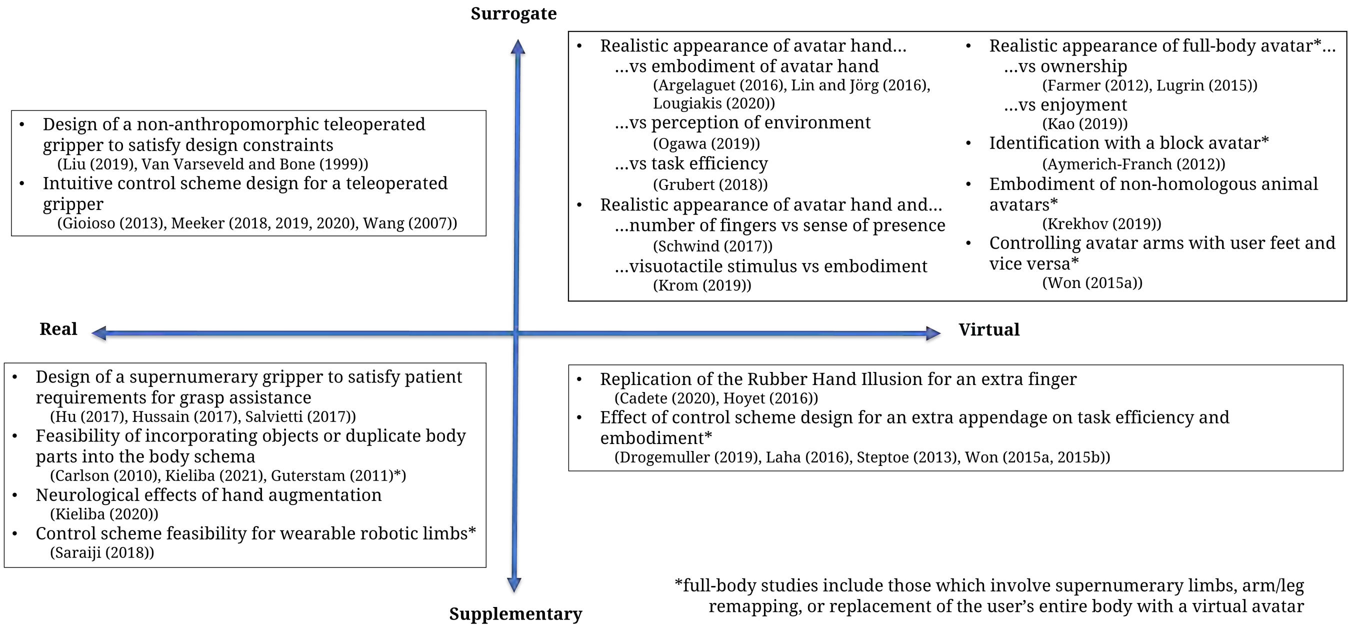

Figure 2: A collection of NAH studies in both physical and virtual, supplementary and surrogate domains. In the virtual/surrogate quadrant where there exist a paucity of hand-focused studies that interpret "non-anthropomorphism" as involving a non-homologous mapping rather than an unrealistic appearance, a second column of studies with full-body non-anthropomorphism have been included. All full-body studies are marked with asterisks.

to create a definition for "non-anthropomorphism" that requires an invented control scheme to map between user and NAH. We describe the components required for a functional NAH system along with relevant design considerations, then present established metrics for evaluating an NAH system's performance. Finally, we conclude with a discussion on the relevance of NAHs to further research areas.

2 OVERVIEW OF NAH-RELATED LITERATURE

In this section, we briefly survey prior literature on the design and evaluation of NAHs, with a more detailed discussion of system and experimental components in section 3. Our inclusion criteria for papers was their use of a non-anthropomorphic avatar or device, with a deliberate focus on hand-oriented experiments rather than full-body non-anthropomorphism in order to constrain our scope to the body part that is most commonly used to teleoperate real or virtual devices. With particular interest in NAH studies that explicitly describe the control mapping between the user's hands and the NAH, we categorized the NAHs we found into those that exist in physical reality (PR) and those in virtual reality (VR), noting that the mechanical constraints of PR strongly influence the NAH forms and control schemes available in that domain. Similarly, we noted a difference in control scheme constraints between NAHs which augment or supplement the user's hand and ones that act as surrogates, entirely replacing it. Control schemes for supplementary NAHs must avoid interfering with normal hand motion, whereas surrogate NAHs are able to take control inputs from the primary motions of the hand. Figure 2 shows the 34 NAH studies we collected, organized by physical/virtual and surrogate/supplementary characteristics.

Because of a relative dearth of hand-focused experiments in the supplementary and virtual quadrants, we supplemented those areas with full-body non-anthropomorphic studies. In particular, we chose full-body experiments that involved a change in topology or a remapping of controls between the user and their avatar, rather than those which attributed "non-anthropomorphism" to avatars based off of the realism of their appearance. These full-body studies are marked by asterisks in Figure 2. We discuss each of the above citations in the sections below.

3 COMPONENTS OF AN NAH SYSTEM

The components essential to an NAH system in the aforementioned studies are listed in Table 1, along with the metrics most commonly used for evaluating system performance. Each of these components is modular, and can be used as the independent variable for an experiment on features that improve user experience and performance of the NAH system. It is worth noting that while feedback schemes and training protocols may be omitted from the set-up, excluding these parameters from the explicit design does not mean that there is no feedback nor training procedure. In-depth explanation of each of these components is provided in the sections that follow.

The performance metrics listed in Table 1 represent the dependent variables used by researchers in different taxonomical quadrants to measure the performance of an NAH system. Although

Table 1: System Components and Performance Metrics Associated with Non-Anthropomorphic Hands in Literature

Components:	Performance Metrics:
An NAH with a defined form and motion profile	Mechanical characterization of design
	Speed/accuracy of task performance
Hardware providing the control (and feedback) interface	Cognitive/behavioral metrics:
	· User preference
Control scheme	· Embodiment/limb ownership
(Feedback schemes)	· Cognitive workload
(Training protocol)	· Presence (for VR/teleoperation studies)
	· Behavioral changes
	Adaptation/Learning metrics:
	· Behavioral changes
	· Feasibility of learning a control scheme
	· Speed/trajectory of learning curve

studies tend to focus on either user experience or objective efficiency, depending on the quadrant, we recommend gathering both kinds of data regardless of the NAH's classification to enable knowledge transfer between disciplines and across quadrants [83]. Recommendations for specific behavioral/functional metrics are found in Section 4.

3.1 Form of the NAH

The form of the NAH is often used as the independent variable for experiments in the virtual/surrogate category, as VR supports faster iteration through forms than physical prototypes generally allow. However, prior experiments in this quadrant have often focused on "non-anthropomorphism" in terms of the realistic appearance of the hand [3, 25, 51, 54, 55]. Our definition of "non-anthropomorphic" is bolder: regardless of appearance, a non-anthropomorphic form must differ from human topology and/or movement dynamics to an extent that a control scheme must be explicitly specified. Examples of this type of non-anthropomorphism include full-body experiments such as [46], where users inhabited animal avatars with homologous and non-homologous limb arrangements; [1] and [81], who used the user's feet to control their avatar's hands and vice versa; and in the hand-focused experiment conducted by [74] where users experienced different numbers of fingers on their virtual hand.

The discerning reader will notice that with two exceptions [5, 78], all NAHs shown in Figures 2 and 3 are variations of "a gripper with an abnormal number of fingers." NAHs in the surrogate category tend to subtract fingers; NAHs in the supplementary category tend to add them. While this adherence to the general topology of a human hand may be useful for preliminary investigations into the effect of hand anomalies on limb ownership on the one hand and provide a convenient reference point for generating feasible control schemes on the other, this figure must not be misconstrued as a representative sample of *all possible* NAH shapes.

A broader (but not exhaustive) list of the range of NAH shapes must include grippers that do not rely on a fingered topology (e.g. loop or basket grippers [69], tentacles [17], or a soft jamming gripper [18], as shown in Figure 4), NAHs for non-grasping tasks, bio-inspired NAHs (such as wings and flippers), and NAHs inspired by mechanical devices or machines (e.g. ones that spin or extend/retract [33]).

NAHs may also differ from human hands by their motion or dynamics, rather than by their structure. Examples of this kind of non-anthropomorphism were shown by [81] in a full-body study remapping control of arms to legs and vice versa. Examples in the NAH domain are shown in Figure 4e, g-h, including a NAH with joints that bend in unfamiliar directions, and one with fingers that change length [7]. Another example is the tentacle-fingered NAH shown in 3c, which is loosely hand-shaped but has the compliance and dynamics of a much softer structure. Regardless of whether an NAH differs from a human hand in shape, dynamics, or both, operating an NAH can be likened to operating a marionette [6]. Just as the marionette's motion is translated from the actions of the puppeteer's hand by a control bar, a NAH is also controlled by the motion of a user's hand—only, the mappings are defined by strings of code.

3.2 Hardware Interface

Hardware interfaces are an uncommon independent variable for an NAH experiment. However, [8–10] suggest that hardware may critically impact successful embodiment of an anthropomorphic robotic wearable, and this same reasoning holds for the non-anthropomorphic devices and avatars under discussion here. Despite its importance, different types of hardware are rarely compared within an NAH study. Instead, it is presumed that the selected hardware interface is adequate to support the NAH study and is maintained across all conditions.

Hardware interfaces for virtual NAHs require a headset display and motion tracking sensors for hand position. Most virtual NAH experiments used a camera-based system to track hand motion rather than utilizing hand-held controllers [3, 38, 51, 67, 74]. This design choice provides more freedom of hand movement, but provides no tactile feedback to the user. An exoskeleton was used by [47] to enable both hand tracking and force feedback. Other methods of capturing hand motion for both PR and VR experiments include datagloves [62, 63, 79], EMGs [40, 62], and pressure pads [2, 43].

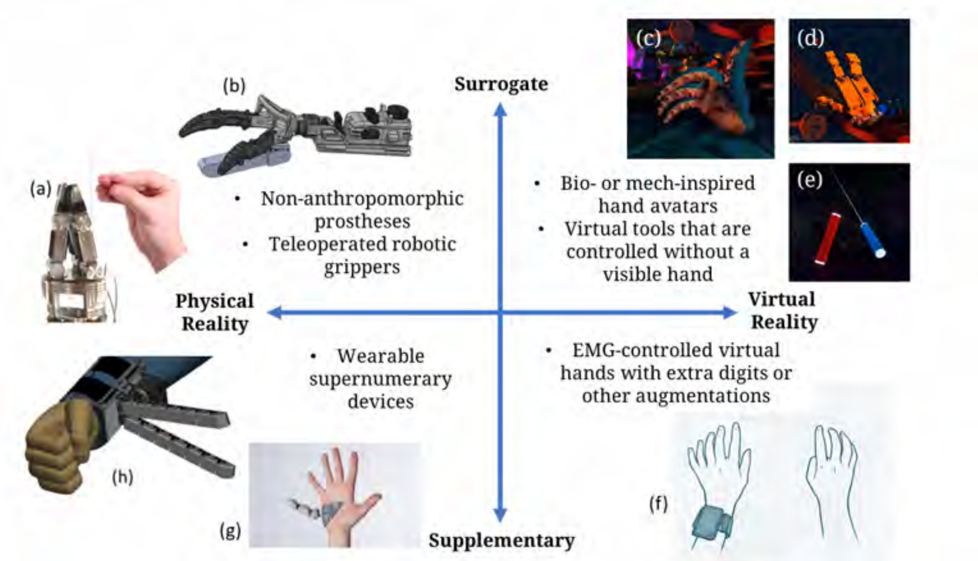

Figure 3: Examples of existent NAHs and where they fit into the PR/VR, supplementary/surrogate classification system include: a) an EMG-controlled, teleoperated claw gripper [61], b) a prosthetic two-fingered hand [50], c) "Elixir," a virtual reality game that transforms a user's hand into an octopus-like hand [24] and mechanical claw (d). e) Some VR games, such as BeatSaber, use tools as avatars that effectively replace the user's hands [5], f) a virtual "sixth finger" might be possible using EMG technology [23], g) "The Third Thumb" project by Dani Clode attaches an augmentative, 3D-printed finger to a hand, controlled by pressure sensors on the user's feet [16, 42], h) A supernumerary grasp-assistance device [40, 71].

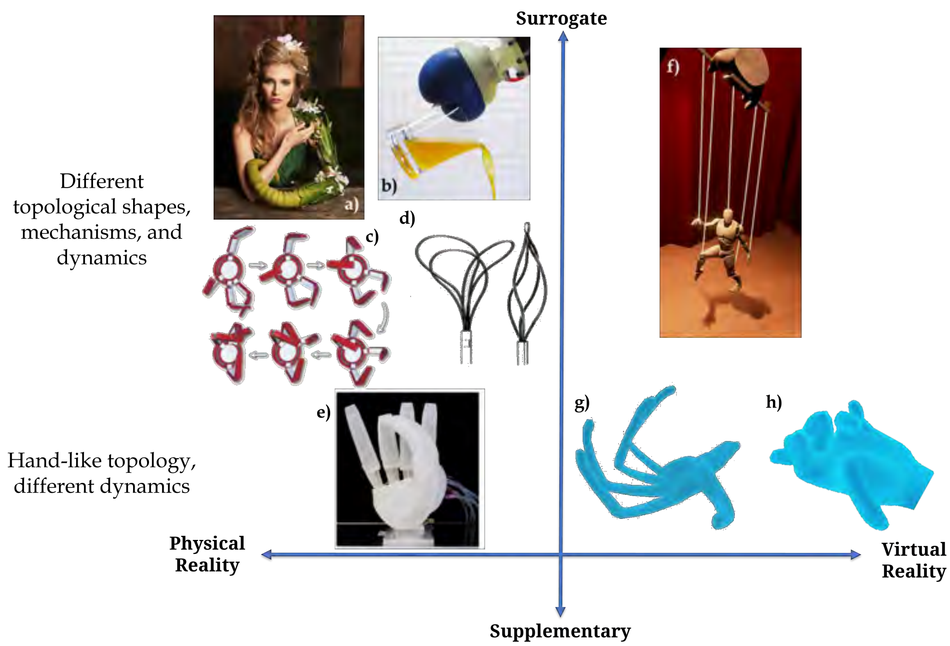

Figure 4: Examples of NAHs that go beyond the "fewer fingers"/"extra fingers" paradigm shown in Figure 3, taken from art and industry. a) Danielle Clode's "Vine Arm" prosthetic [17]. b) a soft jamming gripper [18]. c) a gripper with fingers that are able to rotate around a central palm to conform to the shape of a target object [33]. d) loop and basket retrieval devices for cardiovascular surgery [69]. e) a soft robotic hand [20]. f) a virtual hand controlling the motion of a virtual puppet [6]. g) virtual hands with fingers that can extend beyond their normal length [7]. h) virtual hands with joints that bend in abnormal directions [7].

3.3 Control Scheme Design

Control schemes provide the most universal choice of independent variable across quadrants: if full-body VR studies are included, such experiments are found in every corner of the taxonomy. Supplementary NAHs require novel control schemes by their very nature, as one-to-one mappings between the NAH's structure with the human hand are impossible. Control schemes in the real/surrogate domain tend to be complex, requiring multiple stages of translation in order to transform a hand pose or motion into a functional NAH equivalent [28, 61, 63]. In the virtual/surrogate domain, grasping tasks can be digitally simplified and hand avatars often differ from user hands only in appearance, not by structure. For this reason, virtual/surrogate NAHs often have a direct hand-to-avatar mapping. If the virtual NAH has fewer fingers than the user, a reductive control strategy is used: inputs from the user's extra fingers are simply ignored.

Novel control schemes in the VR domain are more common in full-body studies than hand-oriented ones. Control schemes for a virtual/surrogate full-body avatar were developed by [81] for a humanoid avatar and [46] for a set of animal avatars. The former study, despite the anthropomorphic form, mapped arm motion to leg motion and vice versa for a novel pattern of control. The latter study mapped the user's position indirectly onto various animal forms in order to allow the user to maintain an upright posture, despite the animal avatar's position on all fours. Some animal avatars also had more limbs than the human user; control schemes for these limbs included either 1) controlling multiple avatar legs with each human leg, or 2) animating the avatar legs based on the user's position and orientation. Full-body avatars in the virtual/supplementary quadrant also involved extra tails or limbs;, control schemes were developed that took user motion from degrees of freedom (DOF) irrelevant to the user's primary movements (e.g. wrist rotation, position of the center of the hips) and translated this into the position or angle of the supernumerary limb [22, 48, 76, 81, 82].

The examples in literature demonstrate both the relevance of the control scheme and the nontriviality of its design. A mapping of position or motion from hand to NAH may require expanding or consolidating degrees of freedom, defining useful translations and constraints, exploring the limitations and synergies of ergonomic hand movements, and identifying the motion space and descriptors of interest at the NAH end [27, 64]. While the space of possible control schemes is infinite, common principles emerge. When control schemes map between structures that are similar enough to support one-to-one mappings, the control schemes often leverage that similarity. When tasks are simple—for instance, when the task requires touching a target, or when virtual grasping can be accomplished simply by hovering one's NAH over an object and activating a trigger—then control schemes tend to map a user's individual DOF to particular NAH DOF. When tasks are more complex, control schemes tend to map representations of user intention onto NAH function.

Trends such as these have been labeled by cognitive engineers and biologists, and their vocabulary may be useful here. [64] notes the difference between "high-level," or task-oriented controls, and "low level," or tool-oriented controls. High-level controls simplify a control scheme on the user's end into tasks that the user finds valuable; this eases the cognitive burden on the user by effectively requiring the tool and control scheme to understand the user's intentions. Low-level controls cater toward the machine or device instead, requiring the user to understand the individual subcomponents of actions that are available to the machine. High-level controls provide cognitive simplicity; low-level controls provide versatility. Finding the right balance between simplicity and versatility is a major goal of control scheme design.

The patterns of low-level and high-level control correspond to NAH forms that are "homologous" and "analogous" with human hands, to borrow terms from evolutionary biology. In comparing species across a phylogenetic tree, "homologous" features are those that stem from a common, original ancestor, so that descendant species maintain structural similarity [13]. An example of a homologous structure is pattern of carpals, metacarpals and phalanges that make up the human hand, the flippers of a whale, and the wing of a bat. Homologous limbs may have different functions, but their kinematic similarity lends itself naturally to a control scheme that maps structure to structure—in other words, low-level control mappings. "Analogous" features, on the other hand, are features that have converged towards a common function despite ancestral dissimilarities. Analogous limbs can be seen in the wings of a beetle, a bird, and a bat. While the flight mechanisms for each creature operate differently, the function of the wings remains suitable for flight. Control schemes for analogous NAHs may prioritize task-oriented mappings; for instance, an NAH will grasp an object differently but in synchrony with the user's fisting motion.

3.4 Feedback System

Sensory feedback plays a significant role in motor learning and bodily experience, and is highly recommended for inclusion in a human/machine system intended for embodiment, whether worn or virtual [9, 65]. However, feedback was rarely incorporated explicitly into NAH study designs, with the exception of studies intending to replicate the Rubber Hand Illusion [32, 38, 47]. The Rubber Hand Illusion is a phenomenon where synchronous stroking of a visible rubber hand and the participant's own, hidden hand causes the participant to identify the fake hand as their own. Synchronous visual and tactile stimulation was shown to increase embodiment for both real and virtual hands, even in some cases where the hand's appearance does not match the user's own [26, 70]. It is worth noting that the NAH and user's hand were both held still during the stimulus, and the systems were not evaluated in terms of an improvement in NAH use. While replication of this phenomenon with non-homologous NAHs is in its early stages, these studies demonstrate the importance that sensory feedback can have on embodiment of an NAH.

Feedback is also valuable for skill acquisition and motor learning [9], although few experiments included such feedback explicitly in their designs. [48, 51] and [81] utilized color changes and audible "pops" to inform users of successful task completion, but other studies relied on the native visual and proprioceptive feedback inherent to the NAH. It is important to realize that these intrinsic proprioceptive or somatosensory signals are still significant, and omitting an explicit feedback scheme does not signify a lack of

Table 2: A list of the most prominent subjective metrics conducted in NAH studies, along with established surveys useful to measure each. Surveys are convenient measurement tools; however, they may be subject to post-test subjective biases [68]. For this reason, it may be useful to combine surveys with biometric data and behavioral observations.

Subjective Metric	Relevant Questionnaire
Preference/Enjoyment	(no established questionnaire; use a Likert-scale question)
Embodiment	Avatar Embodiment Questionnaire [30]
	Subcomponents of Embodiment Analysis [12, 44, 53]
Cognitive Workload	NASA-TLX [34, 68]
Presence	Presence and Immersive Tendencies Questionnaire [80]
Usefulness	USE Questionnaire [56]
Satisfaction	QUEST Satisfaction Survey [21]

feedback altogether. [2] demonstrated this in a study where local anaesthetic was used to disrupt somatosensation at the location of a pressure pad used to control a supernumerary robotic finger. A placebo group with no anaesthetic showed higher rates of motor skill acquisition and lower cognitive workload. [9] and [77] recommend exploration of artificially applied feedback, both in terms of schemes and modalities, in order to facilitate motor learning and embodiment further.

3.5 Training Protocol

As with the feedback scheme, the training protocol is an optional element for many NAH studies—however, just as with feedback, excluding it from explicit consideration does not mean that the user undergoes no training process. Instead, learning will be self-guided, or will take place over the course of the study. No existing NAH studies use the training protocol as the independent variable; on the contrary, several studies minimized any training in order to validate the "intuitiveness" of their control scheme design [63, 76]. In other cases, a familiarization period was provided at the start of the study for user exploration and unstructured learning. Some studies assisted this self-guided learning by providing a simplified testing environment for practice [3], a virtual mirror for additional feedback [81, 82], or by delivering instructions on the control scheme beforehand [48, 63]. Only three studies, all in the real/supplemental quadrant, implemented an explicit training protocol [2, 43, 71].

Capturing changes in motor skill over time requires an extended study design that is more difficult to operate than single-session experiments. This may explain its relative dearth among the prior art, and perhaps its omission as a focal point in prior NAH studies. However, NAHs are unusually suited for experiments investigating novel motor skill acquisition in adults, including questions about how methods of information transmission or scaffolding affect rate of learning and skill retention. The recency of the few studies that focus on neuroplasticity and motor learning with NAHs may be evidence of an upcoming rise of a new and fruitful research domain.

4 METHODS OF ASSESSMENT

NAHs perform a dual role as both limbs and tools, which suggests that their performance be evaluated with respect to both their functionality as tools and their integration as a limb. Experiments in all quadrants measured tool-like functionality through objective evaluations of task performance (typically, on grasping tasks). The subjective experience of limb embodiment was measured through user surveys. Additional subjective features of interest generally included one or more of the following: ergonomics and comfort, both for PR wearables and VR motion sickness [40, 48, 55]; enjoyment and satisfaction [40, 41, 74]; presence (for VR systems and real, teleoperated robots) [48, 74, 81]; cognitive workload [1, 2, 72]; and perception of a virtual environment [67].

4.1 Objective Metrics for Assessing System Performance and Functionality

A small subset of PR NAHs evaluate the NAH alone, based on parameters such as size, weight, stiffness, workspace, error, and latency, without including a human in the system [28, 40, 52, 78, 79]. However, in most experiments, measuring objective performance of a human/NAH system requires selection of one or more tasks with quantifiable aims that span the range of operations relevant to the NAH's function. Grasping is the most commonly selected task in the PR domain, with evaluation metrics typically being the number of successful grasps completed on a set of objects relevant to "activities of daily living" (ADLs) (databases of such objects and grasps are listed here: [19, 58, 73]), or adapted from clinical measures of hand function such as the Box and Blocks test or 9-Hole Peg Test [59, 60]. These tests use a singular metric of either time or number of objects moved as the user transfers blocks from one box to another around a barrier or removes and replaces pegs in a wooden board. Using a single metric clarifies the objectives of the test, aids in gamification of the task for the users, simplifies comparison of results across tests and aids in statistical validity.

The difficulty of simulating grasp physics accurately makes evaluation of grasping ability less common and less relevant for virtual NAHs. VR tests tend to evaluate speed or accuracy in target-touching or obstacle-avoidance games [3, 22, 48, 51, 82] or completing a writing or drawing task [31, 74]. Although these are the most common tasks used to evaluate NAH performance, hands perform more functions than grasping, moving, or writing—other common activities include pointing, pressing, manipulating and communicating—and NAHs may perform additional functions that would be inaccessible to normal hands. Tasks should be designed to both query the scope of relevant NAH functions and with the limitations of the testing environment in mind.

4.2 Subjective Metrics for Assessing System Performance and Functionality

Embodiment is the subjective feature most prominently measured in NAH studies, both real and virtual. [53] identified three subcomponents of embodiment, "ownership," "agency," and "location," that can be individually queried by Likert-scale questionnaire. Additional subjective features of interest include ergonomics and comfort, both for PR wearables and VR motion sickness [40, 48, 55]; enjoyment and satisfaction [40, 41, 74]; presence (for VR systems and real, teleoperated robots) [48, 74, 81]; cognitive workload [1, 2, 72]; and perception of a virtual environment [67]. Survey questions that have been validated for these subjective measures are listed in Table 2 along with their references.

Alternative indicators of embodiment include: changes in the peripersonal space [11, 35–37, 57], proprioceptive drift [45], and a user's physical response to a perceived threat [3, 32, 51, 54, 55, 76]. One unusual method of measuring embodiment was conducted by [15], based on changes in perceived after-images. Biometric data can also be used as a supplement to surveys, which are convenient and versatile but also subject to post-test subjective biases [68]. Options for physiological metrics, such as ECGs, EEGs, skin conductance, and pupilometry, are detailed in [66, 75] and [68], with particular emphasis on their correlation with questionnaire-measured cognitive workload.

5 DISCUSSION AND CONCLUSION

NAHs in both virtual and physical domains form a bridge between tools and limbs; they effectively transform a user's ability to interact with their environment and may also transform their concept of their body schema, or physical selves. To be useful tools, non-anthropomorphic hands—particularly "non-homologous" NAHs, which are un-human-like in terms of shape and/or movement—will require control schemes that map human motion onto NAH motion.

Development of such novel forms and control mappings requires an understanding of the components that make up a functional NAH system. In this paper, we described those components and how the design of each might contribute to more effective and novel NAHs. We expect that the terminology, components, design considerations, and subjective/objective metrics we have described will enable future researchers to research more advantageous designs and develop new NAHs that are well-suited to their intended tasks and intuitive to their users.

NAHs additionally provide future researchers a valuable platform for investigating scientific questions about tool design, motor learning processes in adults, training and feedback protocols that support acquisition of new motor skills, and our ability to control or assimilate different kinds of body forms. Where such questions are better addressed at the level of full-body non-anthropomorphism, the hand-level experiments collected in this paper provide a conceptual basis of system components and experimental metrics that can be adapted toward analogous full-body experiments.

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