Imaginary Joint: Proprioceptive Feedback for Virtual Body Extensions via Skin Stretch

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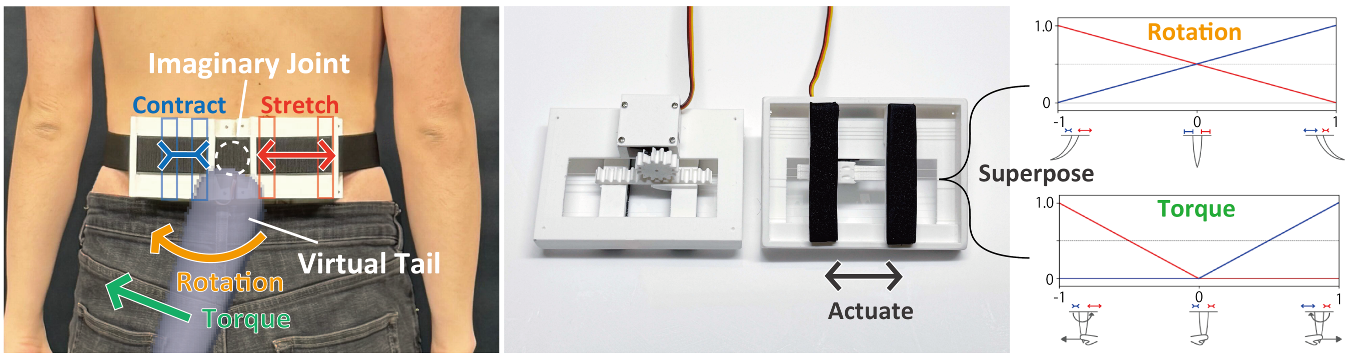

Figure 1: (Left) We propose the metaphor of an "Imaginary Joint" for conveying proprioceptive feedback on virtual body extensions, using localized skin-stretch at the interface between the body and the virtual extension. (Center) Hardware for the Imaginary Joint: A mechanism that stretches and relaxes the skin around the joint. (Right) Feedback Mapping: Converts the angle of the joint and the torque generated by the Imaginary Joint into amounts of skin-stretch. These changes are then superposed and provided as feedback, allowing the user to perceive the angle and torque even without seeing the virtual body extension.

Abstract

Virtual body extensions such as a wing or tail have the potential to offer users new bodily experiences and capabilities in virtual and augmented reality. To use these extensions as naturally as one's own body—particularly for body parts that are normally hard to see, such as a tail—it is essential to provide proprioceptive feedback that allows users to perceive the position, orientation, and force exerted by these parts, rather than relying solely on visual cues. In this study, we propose a novel approach by introducing an "Imaginary Joint" at the interface between the user's actual body and the virtual extension, delivering information about joint flexion and force through skin-stretch feedback. We present a wearable device for skin-stretch feedback and explore informing mappings that convey the bending rotation and torque of the Imaginary Joint. The final system presents both types of information simultaneously by superimposing these skin deformations. Results from a controlled experiment with users demonstrate that users could identify tail position and force without relying on visual cues, and do so more effectively than in the vibrotactile condition. Furthermore, the tail was perceived as more embodied than in a vibrotactile condition, resulting in a more naturalistic and intuitive sensation. Finally, we introduce several application scenarios, including Perception of Extended Bodies, Enhanced Bodily Expression, and Body-Mediated Communication, and discuss the potential for future extensions of this system.

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CCS Concepts

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Keywords

Augmented human, avatar, XR, virtual reality, embodiment, proprioceptive feedback.

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1 Introduction

Body augmentation technology, which adds "body extensions" such as supernumerary arms [45, 52], a sixth finger [47, 71], or a tail [38, 78] to the human form, has recently attracted significant attention and is reshaping human interaction across various domains by enhancing both operational efficiency and expressive capabilities.

In practical scenarios, these technologies contribute to more effective multitasking and supporting human movement [38, 43, 52, 71]. In addition, these technologies are increasingly being applied to social interactions. For example, techniques using a tail [79] or animal ears [61] [1] to convey emotions are currently under investigation, and social VR users are incorporating novel forms of bodily expression—such as using cat ears to express feelings or using a tail to wrap around others. [2]

However, a major challenge in enhancing the operability of extended bodies remains: developing proprioceptive feedback that enables users to intuitively sense the position, orientation, and applied force of extended components without relying solely on visual cues. Typically, humans integrate signals from muscles, tendons, joints [60], and skin [13] to maintain an awareness of limb position, movement and force [48]. In contrast, extended bodies lack innate neural feedback, often forcing users to depend excessively on visual information, which would impose a cognitive burden on them [46]. In virtual bodies, this problem can be even more pronounced than in physical limb extensions, because users cannot perceive physical cues—such as shifts in the center of mass or pressure changes around a mounting point—that normally accompany limb motion. The challenge is most acute for extensions that lie outside the field of view, where visual monitoring is impossible inherently unreliable, such as a tail or the base of a back-mounted extra arm. This limitation can trigger problems in social interaction and practical issues, such as unintended collisions or inefficient task execution. It can also undermine the sense of immersion in the new bodily form. In summary, relying solely on vision-based feedback limits the quality and effectiveness of interactions, highlighting the need for proprioceptive signals that operate independently of visual cues.

Various non-visual feedback methods—including vibration [14, 20, 62], pressure [71], sound [16, 23, 59], and electrical stimulation [55]—have been explored to convey information about augmented body parts in physical and virtual reality environments, telecontrolled robots, and prostheses. For instance, vibrational methods using multiple vibrators and frequencies to indicate a robotic arm's end effector position promote optimal attention allocation [20], yet they offer only coordinate data rather than joint-based posture changes, thereby potentially falling short of replicating natural proprioception. In the field of prosthetics, electrical stimulation of residual nerves or muscles [5, 55] has been used to evoke joint movement perception, although such methods are less applicable to extended body parts that do not naturally exist in humans, as our bodies inherently lack surplus sensory sockets. In VR, prior studies have explored immersive flight experiences and wing haptics using vibration [14], airflow resistance [33], enhanced resistance via exoskeletons [37], and skin-stretch [68] stimulation; however, detailed investigations into the accompanying somatosensory perception are still lacking. One recent study indicates that stretching and compressing the skin near the elbow in sync with a prosthetic hand's movement can mimic innate proprioception [69]. Remarkably, users described the sensation as an "imaginary tendon." Unlike electrical stimulation targeting muscles and nerves, this skin-based approach has the potential to be applied to extended body parts that do not naturally exist in humans.

In this study, we present a proprioceptive feedback system for extended bodies that can be applied in both physical and virtual contexts, with a particular focus on virtual reality scenarios. As a representative case, we focus on the tail—an extension that typically lies outside the user's field of view and thus especially requires proprioceptive cues. The system simulates an "Imaginary Joint" at the interface between the user's body and the extended limb by using skin-stretch to indicate changes in joint angles and torque exerted by the joint. For example, when an extended tail curves to the left, the skin near its base stretches and compresses asymmetrically in the direction of movement (Fig. 1 Left). Likewise, when the tail exerts force against external loads, the skin near its base stretches asymmetrically—employing a metaphor of muscle contraction—to correspond with the level of force exerted. We believe that this "Imaginary Joint" feedback will enable users to perceive the posture and force of the extended body in a way that mimics innate body's natural proprioception, thus reducing their dependence on visual cues. This is not merely a matter of mapping information (like [41]); rather, it is an attempt to construct a fictional sensation—one that lacks a real-world sensory counterpart—that expands how users perceive and embody artificial extensions.

> *Hypothesis: "Imaginary Joint" feedback allows users both to perceive the virtual body extension's posture and the torque it generates, without relying on visual cues, and to increase the sense of embodiment over the extension.*

In this study, we developed a skin-stretch mapping function through exploratory methods to provide feedback on the angle and exerted torque of an Imaginary Joint associated with a virtual tail, and evaluated users' ability to perceive these signals within the final system. To provide feedback on the tail's yaw rotation and exerted torque, we developed a device that stretches the skin on the left and right sides of the waist. Through two preliminary experiments, we investigated an mapping for angle feedback and another for torque feedback. In the main experiment, we compared two feedback conditions—the proposed skin-stretch condition and a vibrotactile condition—across three tasks: the rotation estimation task, the torque estimation task, and the dual estimation task. In the dual estimation task, the actuator movements corresponding to both angle and torque were superposed and presented to the user. The mappings for angle and torque feedback were specifically designed so that users could infer the respective changes in angle and torque based on the superposed stimulation delivered to the left and right sides of the lower back.

The results showed that, across all perceptual tasks, the skin-stretch condition outperformed the vibrotactile condition. Notably, some participants demonstrated consistently high performance even in the dual estimation task, suggesting that the proposed mapping can indeed convey angle and torque information independently yet at the same time to the user. Subjective evaluations also favored the skin-stretch condition, which received higher scores across all dimensions, including body ownership, agency, perceived change, sense of augmentation, enjoyment, naturalness, and intuitiveness. Here, we use the term *naturalness* (and *natural*) to

[1] https://www.necomimi.com/

[2] for example, https://hellojingai3d500.booth.pm/items/6053240

describe the similarity to sensations arising from innate body parts. These findings suggest that the proposed method, which delivers feedback in a manner more closely resembling innate bodily sensations, can support users' intuitive perception and foster a stronger sense of feeling the extended body as part of their own.

The contributions of the paper are as follows:

- We propose a proprioceptive feedback method for extended bodies that is based on an "Imaginary Joint" metaphor, utilizing skin-stretch to provide feedback without relying on visual cues.
- We present an exploratory investigation of mappings that converts virtual body posture and torque into skin-stretch deformation, and we introduce a method to simultaneously convey both posture and torque cues through a single haptic modality.
- Through psychophysical experiments involving a virtual tail, we demonstrate that "Imaginary Joint" feedback outperforms vibrotactile feedback across all measured dimensions, including perceptual accuracy, sense of embodiment, sense of augmentation, enjoyment, naturalness, and intuitiveness.

These findings move us closer to designing interfaces that allow users to operate and perceive extended body parts as if they were innate, potentially accelerating the practical adoption of safe, high-functionality, and enjoyable human augmentation technologies.

2 Related Work

We built on previous studies of extended body technologies in the virtual and physical World, proprioceptive perception, and feedback systems for extended bodies and prostheses.

2.1 Extended Body Technologies in Physical and Virtual Worlds

Supernumerary robotic limbs (SRLs), extra fingers, and robotic tails have been developed to extend the human body's degrees of freedom, thereby reconfiguring the interaction between human bodies and their environment [12, 36]. Early studies explored SRLs to assist in aircraft assembly tasks, including operations such as drilling above the head [10, 44]. Since then, SRLs have been applied in various scenarios, including construction work [63], improvisational music performance [24], rehabilitation support [19], and object recognition for individuals with visual impairments [58]. Extra fingers have also been developed to restore and augment hand function [30, 47, 71, 77]. While fewer in number, robotic tails have been studied for their potential in providing emotional expressivity and physical support [79], as well as assisting in balance control [38].

Users have experienced bodily extension not only in the physical world but also in virtual environments through extended avatars. One of the earliest reports comes from Jaron Lanier, who demonstrated the control of avatars with various morphologies—such as lobsters—by mapping human degrees of freedom onto these non-human forms [27, 76]. He and his collaborators coined the term Homuncular Flexibility to describe the human capacity to learn to control bodies with unfamiliar configurations (i.e., to acquire a new body schema). Subsequent studies have demonstrated that users adapt to avatars with three arms over time, supporting this concept [76].

Adaptation to avatars is explained not only in terms of motor performance, but also through the subjective experience referred to as the Sense of Embodiment [25]. This experience comprises three components: body ownership, sense of agency, and sense of self-location [25], and emerges through multisensory integration processes [29, 31, 34]. Body ownership refers to the feeling that one's body belongs to oneself, sense of agency is the feeling of initiating and controlling actions that produce bodily outcomes (i.e., body agency, as opposed to external agency, where outcomes are perceived as occurring in the external environment [8, 73]), and sense of self-location denotes the feeling of being located at the position of the body within a given environment [28, 31, 50, 70]. Among non-human and non-humanoid avatars, a specific category has been identified by Steptoe et al. as extended avatars—those that retain a human-like base body but incorporate additional parts such as a third arm or a tail [64]. They demonstrated that users could experience a sense of body ownership over a virtual tail, using both subjective and physiological measures [64]. Moreover, the visual appearance of non-human avatars has been shown to modulate users' perception and cognition—for instance, dragon avatars have been reported to alleviate acrophobia [42] and enhance memory for dragon-related vocabulary [15]—highlighting their broad potential for applications spanning both practical and psychological domains.

2.2 Proprioceptive Perception

Through proprioception, we are able to perceive the approximate position of our body without relying on vision, enabling us to avoid obstacles and manipulate objects. The term proprioception, introduced by Sherrington [60], refers to sensations that arise as a result of our own actions, encompassing the senses of position and movement of the limbs and trunk, as well as the senses of effort, force, and heaviness [48]. When we move our limbs, the tissues surrounding the relevant joints—such as skin, muscles, tendons, fascia, joint capsules, and ligaments—undergo deformation [17, 48]. While muscle spindles play a primary role in kinesthetic perception [48], certain cutaneous receptors also provide supplementary information. For instance, it has been reported that stretching of the skin over joints such as the elbow or fingers can induce a sensation of joint movement [7, 13]. Furthermore, Golgi tendon organs contribute to the perception of tension, force, and heaviness [21]. Building on this knowledge, our research aims to evoke innate-like proprioceptive sensations in an extended body by providing tactile stimuli—via skin stretching or compression—to induce the perception of an "Imaginary Joint" at the interface between the innate and extended body.

2.3 Feedback Systems for Extended Bodies and Prosthesis

Sensory feedback from prosthetic limbs has been extensively investigated over many decades due to the significant benefits it provides—such as facilitating intuitive tactile perception, enhancing the adaptation of body image, and improving control [32]. Various methods for delivering feedback from prostheses have been explored. Invasive approaches, such as electrical stimulation of nerves [11, 67], coexist with non-invasive methods including vibrotactile [4, 9, 49], mechanotactile [1], electrotactile [22, 55, 75], skin-stretch [2, 6, 69, 74], and auditory feedback [16, 23, 59]. Among these, the skin-stretch approach has attracted particular attention as an intuitive and effective means to convey proprioceptive information similar to that experienced naturally [2, 6, 74]. Notably, Trujillo et al. [69] reported that participants experienced an "imaginary tendon" sensation at the site of skin-stretch stimulation, suggesting that such feedback can elicit percepts analogous to tendon stretch in the innate body. Building on this insight, the present work extends this illusion beyond the domain of prosthetics and applies it to body extensions, further expanding it to simultaneously convey both angle and torque information.

Similar to developments in the field of prosthetics, recent efforts have focused on integrating physical augmentative devices into the user's body schema by establishing closed-loop systems through control and sensory feedback mappings [46]. In the cases of Metalimb and MetaArm, mappings between the operator's foot movements and the SRL enabled collaborative tasks, such as soldering, to be performed jointly by the user's natural and artificial limbs [52, 54]. Recent work has contributed generative machine learning models for interactive control of a wearable robotic limb that considers both the user's current posture and the model's knowledge of naturalistic human motion behavior [51]. These closed-loop systems not only enhance motor performance but also promote the sense of embodiment and increase user acceptance [46]. Although few studies have investigated what constitutes "better" feedback, one comparative study examined torque-based feedback versus Cartesian coordinate-based feedback for conveying the state of a robotic arm. The results indicated that feedback based on Cartesian coordinates enabled users to more accurately perceive the position of the arm [41]. However, unlike our study, that work conveyed torque magnitude through vibrotactile feedback—utilizing a sensory channel distinct from the innate proprioceptive perception of the human body.

In virtual environments, although still limited in number, recent efforts have begun to explore methods for enhancing immersion in extended avatars by providing control and feedback specifically targeting the additional body parts, reflecting a growing overlap with research on physical augmentative limbs. For instance, Egeberg et al. delivered vibrotactile feedback at the base of a dragon's wing in response to simulated impacts on the wing [14]. In addition, an attempt has been made to represent the sensation of flapping wings for a bird-human using a skin-stretching mechanism [68]. Other studies have used elastic bands [72] or lightweight physical wing [33] components to create a sense of resistance during flapping, thereby enhancing the sense of ownership over the wings. Skin stretch has also been employed to convey bodily transformations and force sensations; Gum-Gum Shooting [81] simulates the sensation of arm extension, whereas QuadStretcher [26] provides users with a realistic sense of force and enhances immersion in tool-based interaction scenarios. However, to the best of our knowledge, proprioceptive feedback for extended body parts in virtual avatars remains largely unexplored, including aspects such as design theory, perception, and subjective experience.

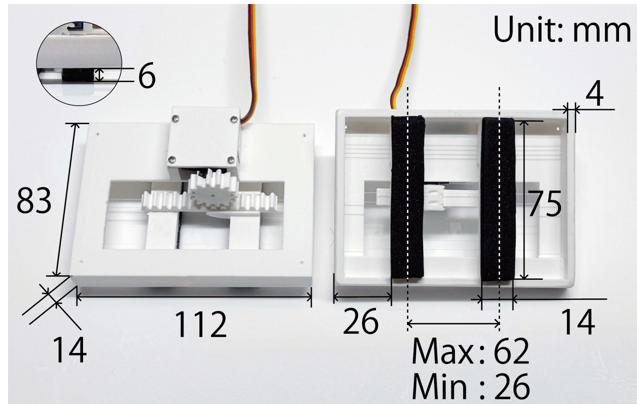

Figure 2: The skin-stretch device. The actuator changes the distance between the two strips of neoprene within a range of 26–62 mm, stretching and compressing the user's skin.

3 Wearable Feedback System

Our concept is to provide feedback on the motion and forces of a virtual body extension in a natural (i.e., with sensations akin to those of an innate body) and intuitive manner. We realize this by deforming the skin near the Imaginary Joint as if that skin and its underlying muscles were moving in the way they would in a natural joint.

For the proof-of-concept, we developed a device to represent an Imaginary Joint's one degree-of-freedom (1DoF) motion (lateral movement/force). Since the joint's side-to-side swaying requires the skin to stretch and compress on both sides, two skin-stretch actuators were used for this 1DoF representation. Moreover, to support various scenarios involving virtual or physically extended body parts, the design was made wearable rather than fixed (e.g., chair-mounted [18]). Although extended parts may include elements such as tails, extra arms, or ears, we chose to focus on the tail first, as its overall state can largely be inferred from feedback at its single base joint and it is commonly not visible to the user. Since virtual tails or tail-like devices are commonly mounted around the waist-to-hip region, the Imaginary Joint was positioned at the user's waist, and our skin-stretch device was designed to be attached to both sides of the back waist. To achieve sufficiently robust skin deformation, the device was mounted directly on participants' bare skin.

The device is shown in Fig. 2. It stretches the skin by operating a rod-shaped actuator in parallel with the skin via a rack and pinion mechanism (Fig. 1 Left). The device housing was 3D printed using ABS material. The overall size (see Fig. 2 for dimensions) of the device was chosen to provide sufficiently large stimulation over the waist area. Each unit weighed 83 g, including a 28 g cover serving as a mounting bracket for attaching the device to a belt. Its design is inspired by previous research on prosthetic feedback [69], where a nylon line supports the actuator. At the skin–actuator interface, 6 mm-thick high-friction neoprene foam (Kleemeiero brand) was used to conform to the diverse contours of the user's back. To represent the virtual joint, the device is mounted on both sides of the joint's rotational axis (Fig. 1 Left). The drive signal is transmitted via a wired connection from an Arduino Duo situated away from the user's body.

During the experiment, the device was securely fixed to a belt via the mounting bracket (Fig. 1 Left), applying a normal force of approximately 30–50 N perpendicularly to the skin. It should be noted that the skin-stretch experienced by the user does not perfectly correspond to the device's actuation; however, the combined effect of the pulling force from the neoprene foam's elasticity and the actuator's displacement provided additional perceptual cues—beyond the mere magnitude of skin deformation—for the user.

4 Informing Mappings for the Imaginary Joint

An mapping for skin-stretch feedback that represents both the Imaginary Joint's angle—located at the base of the tail—and the corresponding generated torque was chosen based on two preliminary experiments. Since these mapping functions would ultimately be superposed, we selected them such that the combination of deformations on each side would retain sufficient perceptual information to allow the original deformation vectors—S_{rot} and S_{torque}—to be inferred:

$$S_{\text{rot}} = \left(S_{\text{rot}_l}, S_{\text{rot}_r}\right),$$

$$S_{\text{torque}} = \left(S_{\text{torque}_l}, S_{\text{torque}_r}\right).$$

Here, S_{rot} represents the actuator changes on the left and right sides associated with rotation, while S_{torque} represents the actuator changes on the left and right sides associated with torque.

In Preliminary Experiment 1, we identified an mapping to determine S_{rot} corresponding to the rotational magnitude, whereas in Preliminary Experiment 2, we identified an mapping to determine S_{torque} corresponding to the torque. Both preliminary experiments were conducted with participants recruited from within the laboratory; these individuals possessed greater knowledge and experience in haptic and human-augmentation technologies than the general population.

It should be noted that this study does not attempt to recreate real-world sensations; rather, it seeks to construct fictional sensations. Consequently—just as in prior researches on somatosensory feedback from extended bodies—users must learn the mapping between the skin stimulus applied to the waist and the corresponding physical quantity. Without such learning, they can sense that a stimulus is "strong" or "weak," but they cannot judge the absolute tail angle or torque it represents.

4.1 Mapping for Conveying Rotational Magnitude

In Preliminary Experiment 1, participants were asked to experience and rank several mappings (Fig. 3) for modulating S_{rot}. The tail could bend up to 90° to either side, and this angle was normalized and used to compute S_{rot}. In Conditions 1 and 2, the two devices moved synchronously at all times, whereas in Conditions 3-6, the movements were temporally distributed between the devices: each time the tail tilted to one side, only the device on that side moved. Conditions 1, 3, and 5 simulated the skin extension expected at the Imaginary Joint—specifically, when the tail tilts to the right, the skin on the left side of the waist is extended. In contrast, Conditions 2, 4, and 6 reversed the direction of actuator displacement compared

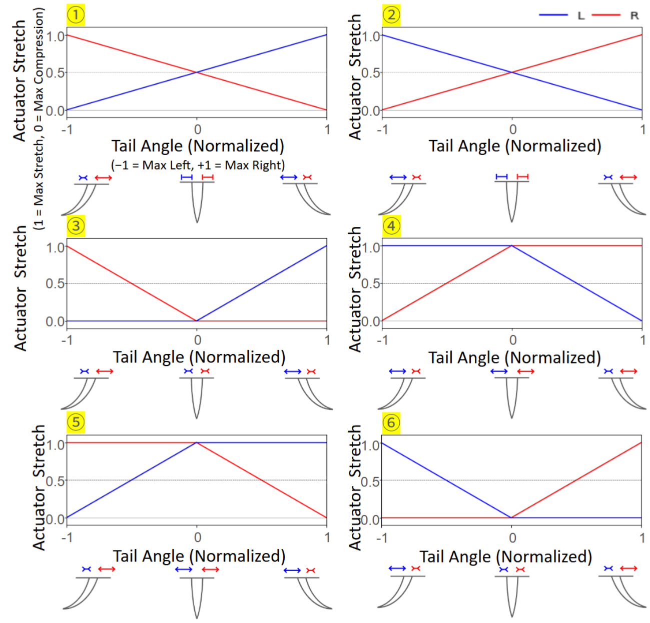

Figure 3: The Mappings for the actuator stretch, S_{rot}, corresponding to tail rotation used in Preliminary Experiment 1.

to Conditions 1, 3, and 5. These conditions simulated a positional shift of the waist skin at the Imaginary Joint—namely, when the tail tilts to the right, the skin on the left side of the waist is drawn toward the right. Participants then ranked these mappings, and their comments were collected for analysis.

In the virtual reality environment, participants could freely switch between multiple tail operating modes and several S_{rot} feedback mappings (Fig. 4). For approximately ten minutes, they engaged in exploring and identifying mappings they preferred. To explore various scenarios, five tail operating conditions were implemented. In the *Swing mode*, the tail swung in response to waist movements. In the *Mapping mode*, the tail rotated according to the horizontal positional movement of the left hand. In the *Animation mode*, the tail oscillated periodically following a predetermined animation. In the *External Control mode*, the tail was actuated left and right via keyboard input by the experimenter, during which a "ghost hand" appeared to apply lateral forces to the tail; an arrow indicating the magnitude of the force was also displayed. In the *External Control Force* mode, the tail was controlled in the same manner, but its movement gradually slowed down as the angle increased. The ghost hand turned red, and the arrow indicating force magnitude grew larger with increasing angle. This visual representation illustrated that the joint generates torque to resist external forces, and that the applied force increases accordingly. Participants could switch between tail operating conditions by touching the corresponding cube on the left side of the VR space, and they could switch the mappings by touching the corresponding cube on the right side.

In all experiments through this paper, the VR research platform was developed using Unity 2022 for the Meta Quest 3 and operated on a gaming laptop equipped with an Intel Core i7 CPU and an

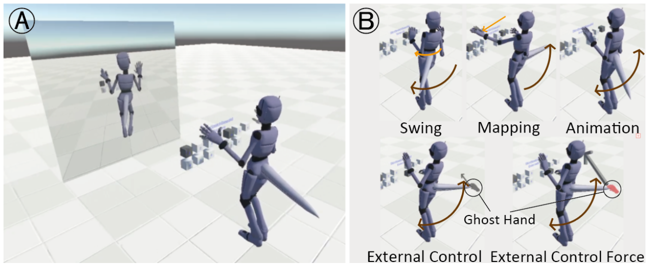

Figure 4: A: VR scene of Preliminary Experiment 1. Participants can freely switch between six feedback mappings and five tail operating modes. B: Each of the tail operating modes.

NVIDIA GeForce RTX 3080 GPU. Participants' hand movements were captured via the Quest's camera-based hand tracking, and the full-body motion of the avatar was controlled using inverse kinematics. To eliminate confounding cues, the avatar—including its tail—was rendered in a neutral, robotic style. A lifelike appearance could have introduced unintended visual signals, such as texture changes or mesh stretching during animation, that might bias participants' interpretation of the feedback. By removing visible skin deformation, the robotic model minimized any influence from specific biological forms.

Nine participants (8 male, 1 female; mean age = 28.7, SD = 10.3) participated in this study. Condition 1 was most frequently chosen as the best and was ranked in the top three by all participants except one. Although Condition 2 was the next most frequently selected as best, preferences varied across participants. Comments regarding Conditions 1 and 2 included phrases such as "moved smoothly" and "was intuitive", supporting the superiority of continuous motion feedback. In contrast, Conditions 3-6 were less favored, with participants noting that "it felt as if there were two tails" and "did not feel smooth", indicating that temporally distributed feedback was generally less preferred.

Based on these findings, we selected Condition 1 as the S_{rot} condition for the main experiment.

4.2 Mapping for Conveying Torque Magnitude

In Preliminary Experiment 2, several mappings (Fig. 5) were evaluated for determining S_{torque} based on the reaction torque generated when an external force was applied to the virtual tail. The torque was normalized using the absolute value of the maximum virtual torque applied to either side, and the resulting value was used to compute S_{torque}. In Conditions 1 and 3, the skin on the forced side compressed significantly, rendering the muscle contraction. In Conditions 2 and 4, the skin on the forced side was greatly extended, which reflects the force experienced as the muscle and tendon are being stretched while the muscle attempts to contract. In Conditions 1 and 2, the skin on the side opposite to the force direction was either stretched or compressed. In Conditions 3 and 4, as a metaphor for co-contraction of muscles counteracting the external force, the skin on the tilted side also moved slightly. Participants were instructed to focus on these feedback stimuli and to form a mental model of the underlying bodily state based on the sensations they perceived.

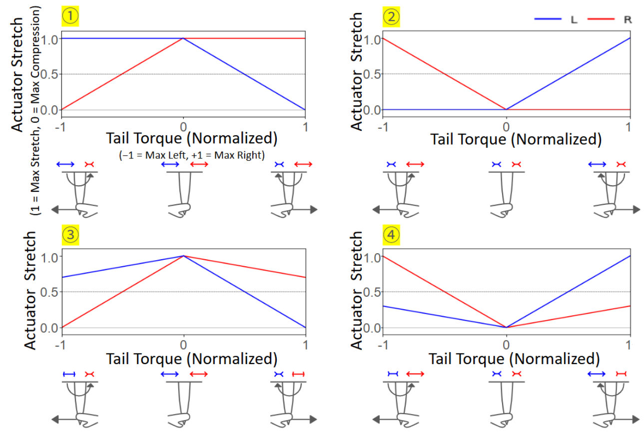

Figure 5: The conditions for the actuator stretch, S_{torque}, corresponding to tail torque used in Preliminary Experiment 2.

The tail was operated in a manner similar to the *External Control Force mode* used in Preliminary Experiment 1; however, the degree of tail movement varied depending on the magnitude of the applied force, which participants could infer from the redness of the ghost hand and the size of the force-indicating arrow. To account for various scenarios involving tail motion, three operating conditions were implemented: in one condition, the tail rotated up to 60°, depending on the direction and magnitude of the torque; in another, it rotated only 5°; and in the final condition, it remained stationary. Participants could freely switch between the four feedback mappings and the three operating conditions via the VR user interface, as in Preliminary Experiment 1. They spent about ten minutes trying out different mappings to identify the ones they liked best.

Nine participants (7 male and 2 female; mean age = 32.3, SD = 11.2) participated in this study. Condition 2 was most frequently chosen as the best (n=6). The other conditions received overall evaluations that were roughly similar to each other, yet lower than that of Condition 2. Condition 2 garnered comments such as "I felt a sense of my muscles being stretched" and "I strongly sensed the directionality." Interestingly, one participant remarked that "the sensation in Condition 2 was similar to the hanger reflex" [3]. In contrast, in Condition 1, some participants commented, "I feel the tail in the opposite direction." Overall, participants tended to perceive the feedback in Condition 2 as natural. Conditions 3 and 4, which attempted to induce a co-contraction sensation, resulted in both sides moving simultaneously, which merely became noise for perception and immersion.

Based on these findings, we selected Condition 2 as the S_{torque} condition for the Main Experiment.

5 Experimental Evaluation

5.1 Experiment Overview

We evaluated the performance of the feedback system—designed based on the concept of an Imaginary Joint—to convey both the motion and force of an extended body. Twenty-one participants were recruited to experience the state of a virtual tail (its yaw rotation and corresponding torque) via the feedback device. As a baseline condition, conventional vibrotactile stimulation was employed. To assess perceptual accuracy, participants were asked to estimate the tail's rotation, the torque exerted by the tail, and a combination of both, in response to the given stimuli. The experimental protocol consisted of three tasks: the rotation estimation task, the torque estimation task, and the dual estimation task. In the first task, a rotation-only stimulus (without torque) was presented; in the second, a torque-only stimulus (without rotation) was administered; and in the final task, a superposed stimulus involving both rotation and torque was delivered. Following the tasks, participants completed a seven-point Likert scale questionnaire assessing the sense of embodiment (adapted from the VEQ [50]) and the sense of augmentation, enjoyment, naturalness and intuitiveness of the sensation. Finally, a semi-structured interview was conducted to gather insights on the overall experience and user preferences. Participants were sequentially asked which condition they preferred, which one felt more similar to an innate bodily experience, and which one felt more intuitive. Based on participants' responses, their experiences were further explored through flexible follow-up questions. This study was approved by the local ethics committee.

5.2 Experimental Conditions

Two feedback modalities were implemented: the proposed skin-stretch method and a conventional vibrotactile stimulation approach. For the skin-stretch condition, the overall stimulus (S_{all}) was defined as the arithmetic mean of the rotation stimulus (S_{rot}) and the torque stimulus (S_{torque}):

$$S_{\text{all}} = \frac{S_{\text{rot}} + S_{\text{torque}}}{2}$$

In the vibrotactile condition, the voltage applied to the vibrator was adjusted to be proportional to S_{all}. That is, when $S_{\text{all}} = 1$ (corresponding to the maximum skin stretch in the skin-stretch condition) the vibrator received its maximum voltage. A Vp210 voice-coil vibrator (Fig. 6) driven by a 200 Hz sine wave was selected, as voice-coil devices allow precise control of both stimulus amplitude and frequency, which influences perceived intensity, while also providing stable and powerful output suitable for consistent vibrotactile feedback. The overall dimensions of the unit and its cover were the same as those in the skin-stretch condition, and each unit weighed 103 g, including a 28 g cover. This feedback method was motivated by earlier work in which the position of a robot arm were converted into vibration intensity for haptic feedback[41]. To deliver bilateral stimulation to the user's waist, two vibrators were used. To ensure that participants could perceive the vibration corresponding to $S_{\text{all}} = 0.2$, the gain of the audio amplifier connected to the Vp210 was adjusted. This calibration criterion was chosen to avoid excessive high gain by taking into account the heat generated by the vibrator. As a result, the maximum voltage applied to the vibrator ranged from approximately 2.7 V to 5 V.

5.3 Participants

Twenty-one participants (18 males and 3 females) with a mean age of 25.7 years (SD = 5.8) took part in the experiment. They were openly recruited via social media. Among them, one was left-handed. Eight participants were frequent users of VR equipment; among these, four were social VR players who owned their own avatars. However, none of the participants routinely used extended-humanoid avatars featuring animal ears, tails, or additional arms. Eleven participants had some prior experience with VR, and two were newcomers. In total, eight participants had experience using extended avatars at least once. Each participant received a compensation of 2700 Yen upon completion of the study.

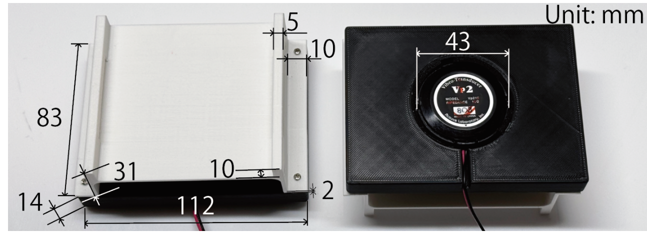

Figure 6: Feedback device for the vibrotactile condition.

5.4 Procedure

Figure 7 illustrates the experimental procedure. Participants first received a detailed explanation of the study and provided written informed consent. Demographic information (including age, gender, and VR experience) was collected via a pre-experiment questionnaire. Participants then wore the feedback system (either skin-stretch or vibrotactile) and a head-mounted display (HMD), with the HMD's inter-pupillary distance (IPD) adjusted for individual comfort. The experiment consisted of two feedback conditions, presented in a quasi-counterbalanced order; eleven participants started with the skin-stretch condition, and ten with the vibrotactile condition.

Participants sequentially performed the rotation estimation task, the torque estimation task, and the dual estimation task. After completing the tasks, participants removed the equipment and completed post-experiment questionnaires. Following a three-minute break, participants proceeded to the next condition. Upon completing both conditions, participants participated in an interview to assess the overall experience of the proprioceptive feedback related to the extended body.

5.5 Task Design

Rotation Estimation Task. In the *rotation estimation task*, participants estimated the tail's rotation angle based solely on the feedback stimulus. A total of 11 distinct stimuli were defined at 18° intervals, ranging from −90° to +90°, including 0° as one of the conditions. When ignoring the sign, this resulted in 6 unique magnitudes. These angles were normalized by dividing by 90°, and the resulting values were used to compute S_{rot} in accordance with the graph shown in Fig. 3-1. Subsequently, S_{all} was calculated based on S_{rot}. Based on previous research [41], the task was divided into three phases: an observation phase, a training phase, and a test phase. In the observation phase, participants were presented with 24 stimuli while viewing the back of their avatar on a forward-facing virtual display (Fig. 7). The tail's angle was simultaneously displayed in real time as text. In the training phase, the display, tail, and hollow text were hidden, and participants were required

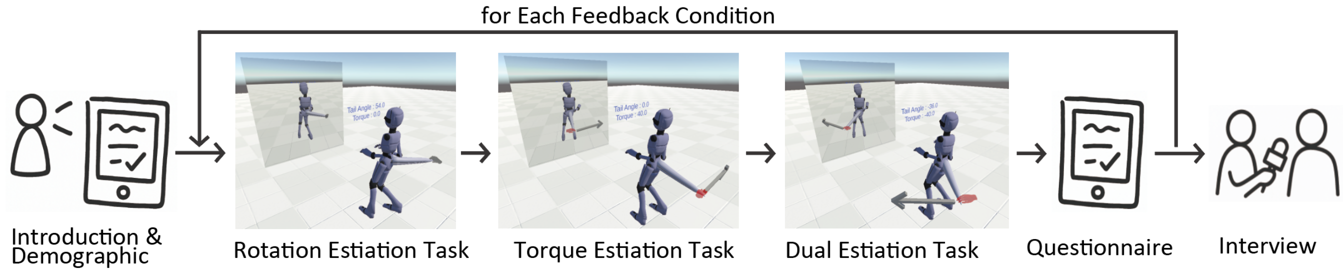

Figure 7: General study procedure. Each image presented during the task corresponds to the observation phase, during which participants could view the avatar's tail movement via a display along with the numerical value representing the actual stimulus magnitude. During the training and test phases, however, the display, tail, and numerical values are hidden until the participant provides an estimate based solely on the tactile feedback.

to estimate the tail's angle from the given stimulus without visual observation of the tail's orientation. After responding, the display, tail, and hollow text were revealed again, allowing participants to calibrate their internal sense of the angle. In the test phase, participants verbally provided an estimated angle based on the stimulus without visual feedback. The correct answer was not displayed.

In all phases, the stimulus was reset to an angle of 0° before each trial, and a delay of at least one second was enforced before proceeding to the next trial. In the observation phase, 24 stimuli were administered; in the training phase, 24 stimuli; and in the test phase, 36 stimuli. Each stimulus, except for 0°, was presented an equal number of times, with the 0° stimulus being presented twice as frequently. In other words, an equal number of stimuli was provided for each absolute angle value. The trials were delivered to the subjects in a predetermined random order. Each test-phase trial received the angle-only accuracy score

$$R_\theta = \frac{1}{1 + \Delta\theta},$$

where $\Delta\theta$ is the number of angle-step errors. For example, if the stimulus was 18° and the participant responded with 72° ($\Delta\theta = 3$), the score was $R_\theta = 0.25$; a response of 0° ($\Delta\theta = 1$) yielded $R_\theta = 0.5$.

Torque Estimation Task. In the *torque estimation task*, participants estimated the torque generated by the tail in response to external forces, while the tail's angle remained fixed at 0°. Eleven torque levels, ranging from −50 N·m to 50 N·m in 10 N·m increments, were tested using a protocol analogous to that of the rotation estimation task. These torques were normalized by dividing by 50 N·m, and the resulting values were used to compute S_{torque} in accordance with the graph shown in Fig. 5-3. Subsequently, S_{all} was calculated based on S_{rot}. Each test-phase trial was scored with

$$R_\tau = \frac{1}{1 + \Delta\tau},$$

where $\Delta\tau$ is the number of torque-step errors. For example, if the stimulus was 50 N·m and the participant responded with 30 N·m ($\Delta\tau = 2$), the score was $R_\tau = 0.33$. In the training phase, a ghost hand was displayed to visually represent the externally applied force; its redness increased proportionally with the applied force (Fig. 7 Torque Estimation Task).

Dual Estimation Task. In the *dual estimation task*, participants were required to estimate both the tail's rotation angle and the opposing torque simultaneously. As in the previous tasks, 11 levels each for rotation and torque were used. S_{rot} and S_{torque} were calculated in the same manner as in the respective single-modality tasks, and the final actuator displacement S_{all} was derived accordingly. In a natural scenario, the direction of the applied force would result in a corresponding tail rotation; therefore, the signs of rotation and torque were matched. There were 36 unique combinations of the absolute stimulus values (6×6). In the combined observation and training phases (totaling 48 trials), each combination appeared at least once and at most twice. In the test phase, all 36 combinations were presented. Half of the trials were randomly assigned stimuli with negative values. In the analysis, the two-dimensional accuracy score was

$$R_{\text{2D}} = \frac{1}{1 + \sqrt{\Delta\theta^2 + \Delta\tau^2}},$$

while the one-dimensional accuracy scores R_θ and R_τ were computed as above. All other procedural aspects were consistent with those described for the single-modality tasks.

In each trial across the three tasks, the stimulus transitioned over 0.5 s from the actuator state corresponding to $(0°, 0\,\text{N}\cdot\text{m})$. During the observation and training phases, the stimulus was presented until the participant signaled, after which it returned to the initial state over another 0.5 s. In the test phase, the stimulus was presented until the participant responded or until 5 s had elapsed from the onset of presentation. During stimulus presentation, white noise was played through headphones to mask the operational noise of the actuators.

In the vibration condition, vibration was stopped in-between trials to avoid VR sickness, neural impairment, and excessive heating of the vibrator.

Sufficient breaks were provided between tasks to allow subjects to recover from fatigue.

5.6 Questionnaire

Subjective measures were obtained via questionnaires assessing multiple facets of the user experience (Tab. 1). Specifically, the sense of embodiment was evaluated using items Q1–Q6, which were adapted from the Virtual Embodiment Questionnaire (VEQ) [50] to suit the context of the virtual tail, albeit with the exclusion of several original items. In addition, Q7 was introduced to measure the sensation of body augmentation, reflecting the extension of the

Table 1: Questionnaire items evaluating embodiment and user experience.

ID	Category	Question
1	Ownership	It felt like the virtual body parts were my body parts.
2	Ownership	It felt like the virtual tail belonged to me.
3	Agency	The movements of the virtual tail felt like they were my movements.
4	Agency	I felt like I was controlling the movements of the virtual tail.
5	Agency	I felt like I was causing the movements of the virtual tail.
6	Change	I felt like the form or appearance of my own body had changed.
7	Change	I felt like the size of my own entire body had changed.
8	Augmentation	I felt that a new body part was added while the structure of my innate body remained the same.
9	Enjoyment	How much did you enjoy the interaction?
10	Enjoyment	How much fun was the interaction?
11	Naturalness	How naturally were you able to feel the sensation of a virtual tail in a way similar to that of an innate body?
12	Intuitiveness	How intuitively were you able to feel the sensation of a virtual tail?

user's physical experience. The degree of enjoyment was captured using items Q9 and Q10, while Q11 and Q12 were incorporated to assess the naturalness and intuitiveness of the interaction, respectively. For each category, the average score was used for analysis.

5.7 Results

Figure 8 shows the scores for each condition and each task. A paired t-test was used to analyze the results. The normality assumption was not violated (Shapiro-Wilk test). The results show that, overall, the skin-stretch condition yielded significantly higher scores than the vibrotactile condition (Angle: $t\ (20) = 4.34$, $p < .01$, $d = 0.95$, Torque: $t\ (20) = 12.45$, $p < .01$, $d = 2.72$, Dual_Angle:$t\ (20) = 4.57$, $p < .01$, $d = 1.00$, Dual_Torque: $t\ (20) = 2.58$, $p = .02$, $d = 0.56$, Dual: $t\ (20) = 4.86$, $p < .01$, $d = 1.06$). Moreover, estimating each stimulus independently in the dual estimation task resulted in significantly lower scores than when each was stimulated individually (Stretch Condition, Angle vs Dual_Angle: $t\ (20) = 2.89$, $p < .01$, $d = 0.63$, Torque vs Dual_Torque: $t\ (20) = 10.51$, $p < .01$, $d = 2.29$. Vibrotactile Condition, Angle vs Dual_Angle: $t\ (20) = 3.30$, $p < .01$, $d = 0.72$, Torque vs Dual_Torque: $t\ (20) = 5.42$, $p < .01$, $d = 1.18$).

Figure 9 shows box plots of the responses to the questionnaire. A Wilcoxon signed-rank test was conducted for each of the following: Ownership, Agency, Change, Augmentation, Enjoyment, Naturalness, and Intuitiveness. The results indicate significant differences between skin-stretch and vibrotactile conditions (Ownership: $p < .01$, $r = 0.71$, Agency: $p = .02$, $r = 0.51$, Change: $p = .04$, $r = 0.46$, Augmentation: $p = .02$, $r = 0.50$, Enjoyment: $p < .01$, $r = 0.58$, Naturalness: $p < .01$, $r = 0.59$, Intuitiveness: $p < .01$, $r = 0.62$).

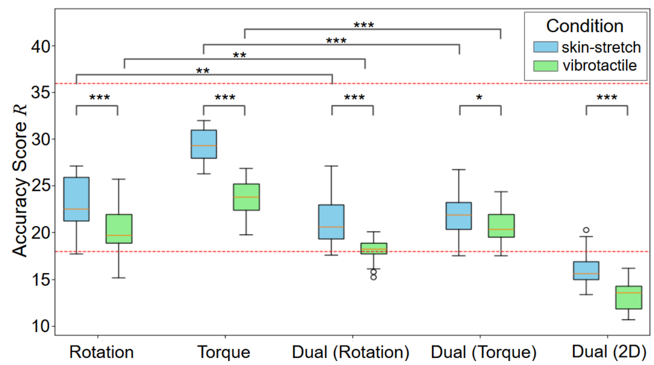

Figure 8: Accuracy scores of the rotation and torque perceptual tasks. The dotted line at a score of 36 indicates perfect accuracy, while the dotted line at 18 corresponds to the level where one error step occurred in each trial. ***Asterisks indicate statistical significance:*** *$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.*

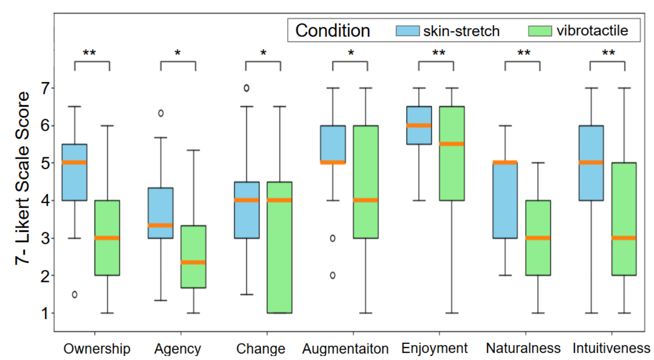

Figure 9: Results of the subjective questionnaire. 7: strongly agree / a great deal; 1: strongly disagree / not at all. ***Asterisks indicate statistical significance:*** *$^{*}p < .05$, $^{**}p < .01$.*

6 Discussion

6.1 Performance and user experience.

The aim of this experiment was to examine the extent to which skin-stretch feedback, based on the concept of the Imaginary Joint, can convey both the tail's angle and the magnitude of torque produced, as well as to assess the subjective quality of the experience. Across all tasks, the results consistently supported the proposed hypothesis.

Clearly, our proposed skin-stretch feedback outperformed the vibrotactile feedback condition in conveying angle and torque information according to the proposed mapping. In the rotation estimation task, skin-stretch feedback achieved a median score of 22.53

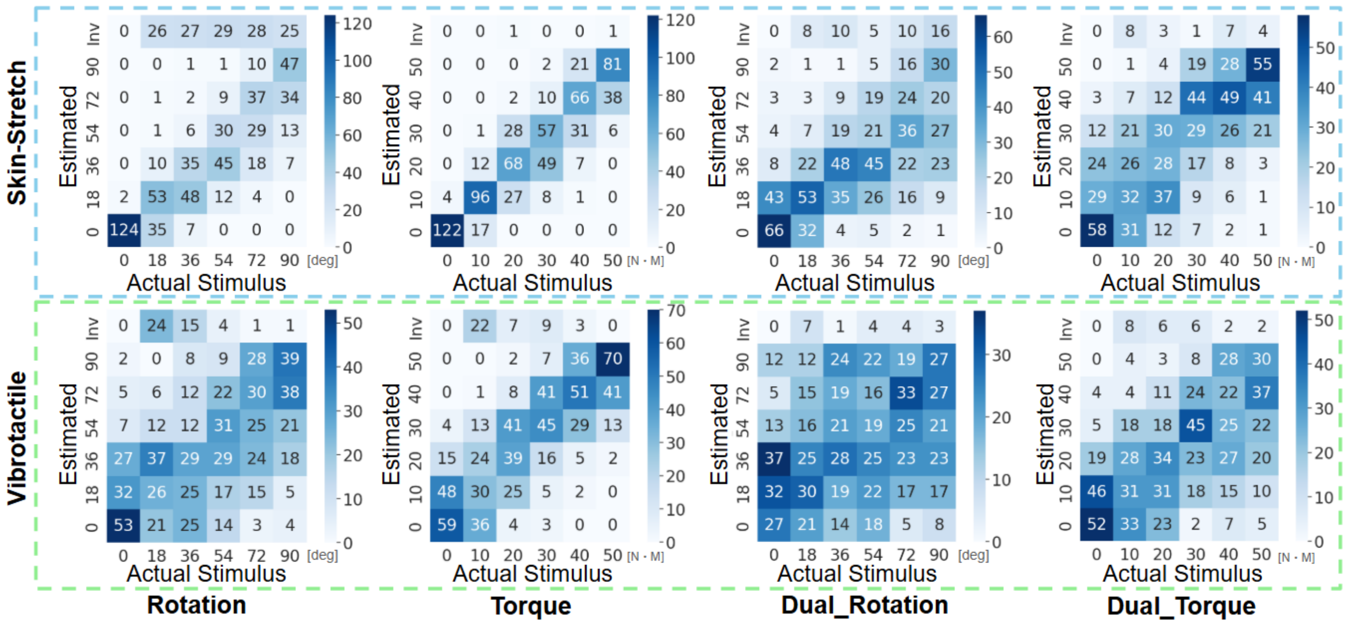

Figure 10: Confusion matrices of rotation estimation task, torque estimation task, and dual estimation task.

points, which corresponds to an error of approximately 0.60 error steps (i.e., 10.8° in this scenario) when computed using the scoring formula. Similarly, errors of approximately 0.23 error steps (2.3 N in this scenario) for torque estimation task and 1.31 error steps for dual estimation task were observed. In contrast, vibrotactile feedback produced errors of approximately 0.82 error steps for rotation estimation task, 0.51 for torque estimation task, and 1.66 for dual estimation task. It should be noted that these unit-based error metrics, derived by converting error steps into angle and torque values based on maximum stimuli of 90° and 50 N·M respectively, are subject to a scaling constant and do not precisely represent the system's inherent perceptual resolution. Nevertheless, these findings suggest that skin-stretch feedback may offer users a more accurate perceptual experience compared to vibrotactile feedback.

During the experiment, frequent instances of subjects confusing the positive (right) and negative (left) directions were observed, prompting further analysis of sign errors. The confusion matrix (Fig. 10) revealed that under the skin-stretch condition, sign errors in the torque estimation task were minimal, although approximately 21% of responses in the rotation estimation task were incorrect across all stimulus magnitudes; whereas under the vibrotactile condition, sign errors tended to occur in both tasks, particularly when stimulus magnitudes were small. This may be attributable to the fact that, in the rotation estimation task under the skin-stretch condition, both actuators moved simultaneously by the same amount, leading participants who focused on the actuators' movement rather than the resulting skin-stretch sensation to confuse which actuator moved in which direction and to map it to the tail orientation. Participant comments support this possibility (e.g., **"if I do not consciously remember which side is shortening and which is stretching, I cannot determine the direction" (P4)**; **"with the skin-stretch condition, it was difficult to sense the direction except when the movement was occurring" (P6)**). However, most participants were able to perceive the state of skin-stretch even in a static condition, according to their comments.

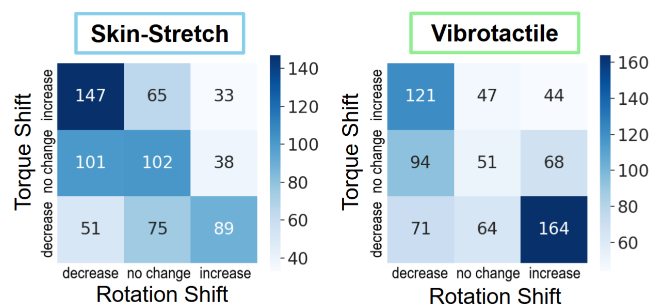

Figure 11: Shift directions of the absolute values for angle and torque in dual estimation task. Trials in which the signs of the stimulus and the estimation were reversed have been excluded.

Moreover, in the dual estimation task, perceptual accuracy decreased compared to tasks assessing each parameter independently. As shown in Fig. 11, which illustrates the directional errors for each stimulus, participants did not simply overestimate or underestimate the stimuli uniformly; rather, they appeared to misattribute the overall intensity of the stimulus to either torque or angle. Additionally, Fig.10 shows that the diagonal concentration in the confusion matrices was less distinct in the dual condition, indicating reduced estimation clarity. Nevertheless, a certain degree of diagonal alignment remained in the skin-stretch condition, suggesting that participants were still able to perceive angle and torque as partially separable dimensions. In fact, five participants achieved

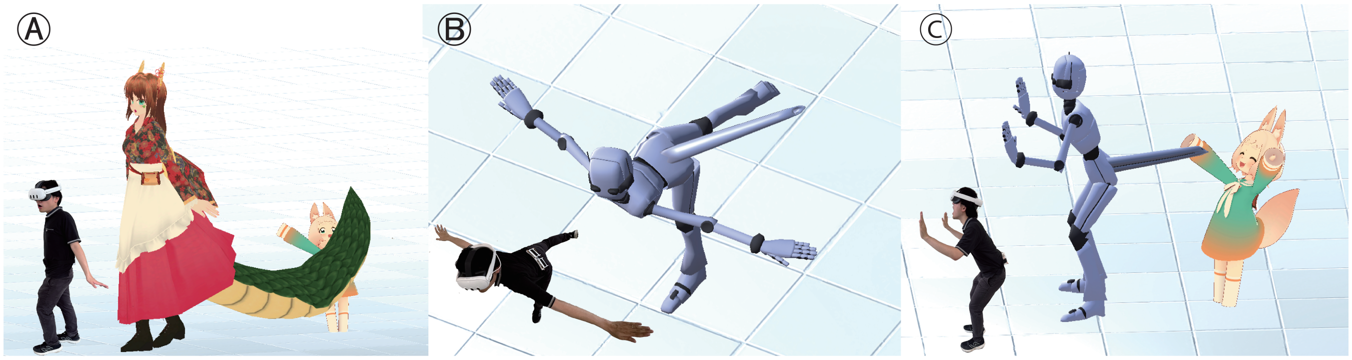

Figure 12: Applications of the *Imaginary Joint*; A. Perception of Extended Bodies: Accurate awareness of the extended body's position allows users to avoid unintended collisions and to detect contact. B. Enhanced Bodily Expression: In ballet and other dance forms, perceiving the extended body's position plays a crucial role in expressive movement. C. Body-Mediated Communication: Even when efferent cues are absent—e.g., when the extended body is operated by another person or by AI—knowing the body's position facilitates communication. The avatar in green clothing was sourced from [35].

scores above 18 in the dual estimation task (Fig. 8), indicating that the combined estimation error for angle and torque did not exceed one step on average. Considering the broad range of possible responses, this level of accuracy can be considered notably high.

The results of the subjective questionnaire indicated that the skin-stretch condition scored higher across all categories, including ownership, agency, change, augmentation, enjoyment, naturalness, and intuitiveness than the vibrotactile condition. Participants reported that the skin-stretch feedback evoked a sensation akin to that of a innate body (e.g., **"I don't have a tail, but the sensation of being pulled felt tail-like" (P8); "It closely resembled what I imagine it would feel like if I had a tail that could move laterally" (P12)**). Moreover, this natural, body-like sensation—beyond simply conveying information—appeared to enhance the sense of embodiment. One participant commented, **"the vibrotactile feedback, although temporally synchronized, was like the vibration feedback of a game controller—conveying signals to the body rather than being perceived as an integral part of it—whereas with the skin-stretch feedback, I felt the tail was more a part of my body" (P15)**. These advantages are consistent with findings on skin-stretch feedback in prosthetics [2, 6, 69, 74] and are particularly valuable because they extend the potential application to extended body that go beyond the innate human form.

Ratings for agency and change tended to be moderate or lower. This is likely due to the fact that, in the experiment, users did not have control over the tail's movements. In more practical applications, where the feedback is integrated with control methods—such as body movement remapping [52, 66]—these evaluations could be improved.

Notably, two participants reported VR sickness only during the vibrotactile condition, attributing it to the vibrations. This suggests that skin-stretch feedback may offer greater comfort for prolonged use in immersive environments.

7 Application Areas

The proposed proprioceptive feedback method, based on the concept of the Imaginary Joint, offers more intuitive and natural feedback than the vibrotactile condition, enhancing both embodiment and task performance. This approach is applicable in a wide range of scenarios involving extended bodies, including virtual reality, human augmentation, teleexistence, and even wearable costumes.

7.1 Perception of Extended Bodies

In social VR, for example, users may choose avatars with non-human features such as cat ears or tails. Our ongoing qualitative research with non-humanoid avatars in social VR has revealed several issues arising from the absence of proprioceptive feedback—for instance, users accidentally stepping on others with extended limbs and tails, or large tails obstructing the view of avatars with shorter statures (Fig. 12). Consequently, there is a demand for feedback that provides awareness of body posture and collisions, as well as enhanced immersion. By applying the Imaginary Joint approach to deliver somatosensory feedback for tails and other extended body parts, these challenges can be mitigated, leading to a more immersive user experience. In addition, the lower incidence of VR sickness reported in the skin-stretch condition compared to the vibrotactile condition suggests that this method may be better suited for long-term use.

In the context of human augmentation, the importance of proprioceptive feedback has also been emphasized. For example, in scenarios where a tail or an extra arm extends from the back, the Imaginary Joint approach can provide feedback about movement at its base—an area that is typically out of sight. This feedback serves as an additional cue, complementing the pressure changes and inertial force that real-world augmentative body parts may produce as side effects.

In a preliminary system combining a robotic tail (length = 33 cm, mass = 260 g, actuated by a Dynamixel XM430-W210) with the Imaginary Joint (Fig. 13), qualitative feedback was collected from three participants. The study had two aims: (i) to compare—and,

Figure 13: Prototype integrating a 1-DoF robotic tail with the Imaginary Joint device.

where feasible, integrate—tail-borne inertial feedback with skin-shear feedback for VR, and (ii) to evaluate the Imaginary Joint's suitability for physically augmented bodies. Participants judged the tail's inertial cues weaker than its size implied, underscoring a trade-off: stronger inertia requires greater mass, which increases latency and safety risk and yields a lower stimulus-to-volume ratio than skin-stretch. In contrast, the Imaginary Joint delivered a clear, high-magnitude stimulus. The tail, however, conveyed motion direction more intuitively than skin-stretch alone. When both cues were presented together, every participant preferred the hybrid configuration, describing a stronger and smoother tugging sensation. Thus, the Imaginary Joint provides compact, safe, and intense stimulation, while the tail supplies reliable directional information; their combination promises a richer perceptual experience. Moreover, the Imaginary Joint can communicate the movements of a physically augmented body more explicitly than the body's incidental inertial forces, further motivating its integration.

7.2 Enhanced Bodily Expression

Proprioceptive cues are beneficial not only in practical scenarios but also in enhancing bodily expression using extended bodies. In contexts such as dance with augmentative limbs [80][3], awareness of the posture of the extended body—just as in classical ballet—is crucial, and proprioceptive feedback may improve the quality of expression. Similarly, in theatrical performances involving fantasy characters with tails or large ears [65], real-time awareness of how these extensions are actually moving in relation to one's intended gestures may reduce anxiety about system responsiveness. Even in virtual environments, bodily expression using non-human or extended-human avatars is becoming more common. For example, when a beast-like avatar wags its tail to express joy, such feedback can likewise support more expressive and confident interactions.

[3] see https://www.youtube.com/watch?v=ywrK1yTYRIA

7.3 Body-Mediated Communication

When users themselves provide motor input to an extended body, it serves as an efferent cue. However, when the movement is initiated by another user or AI, such cues are absent, making afferent feedback essential. For example, in social VR, when another user manipulates a tail attached to someone's avatar, the user may often fail to notice the movement. Providing a sensation such as "the tail was pulled" would enhance bodily interaction in VR. Similarly, in real-world human augmentation devices, scenarios involving collaboration with others or AI—such as in the Fusion[53] system—have been explored. In such cases, being able to perceive the position of an arm controlled by someone else can help reduce cognitive load and support better attentional allocation.

8 Limitations & Future Works

In the present experiment, the actuator movement was linearly correlated with the magnitude of the virtual stimulus. However, by considering human characteristics such as the nonlinearity of perception, it may be possible to further reduce perceptual errors. The confusion matrix suggests that accurate perception becomes more challenging with moderate stimulus levels; thus, increasing the actuator movement in this range could help mitigate perceptual errors. Additionally, to compensate for instability in discerning left from right, it may be beneficial to integrate mechanisms that enhance the sense of pulling in static conditions (for example, by actively incorporating elastic forces of rubber to simulate the skin-pulling force) or to implement systems that provide intuitive left/right cues through means other than skin-stretch (e.g., inertial forces [40]).

Our current prototype is limited to providing feedback for the left-right motion and force of a single-joint tail; however, it would also be useful to provide feedback for multiple directions or to convey the sensation of a multi-joint structure rather than a single joint at the base. While the system could be readily extended to a 2-DoF configuration (tail yaw and pitch), extending it to include the roll direction would require devising a mechanism that stretches the skin around the Imaginary Joint in a rotational manner centered on the joint. A pin-based skin shearing device[18] may be suited for this purpose. Furthermore, for multi-joint applications, approaches that intuitively map multiple Imaginary Joints onto the skin, or that approximate a multi-joint structure with a spline curve—where the curve's shape is represented by the temporal changes in skin-stretch on both sides—should be considered.

Although our prototype was worn directly on bare skin to ensure precise shear deformation, some users—especially in public settings—may be reluctant to attach hardware to sensitive areas like the waist, even if the device can be worn underneath clothing. Wearing the current device over clothing dulls the stimulus, so a key avenue for future work is to develop shear-feedback methods that remain clear and discriminable through garments.

Furthermore, it may be worthwhile to investigate in more detail potential effects of an individual's demographics. Firstly, since the device is attached to the skin, a more detailed investigation is needed to understand how differences in body size might influence the experience. Secondly, some reports suggest that women are more accepting of non-human avatar appearances [56]—or are less sensitive to changes in avatar appearance [57]. Thirdly, none of the participants in this study were habitual users of extended-body avatars in applications such as social VR. Previous research has reported that social VR users can experience phantom sensations even for body parts that do not exist [39], and future research should focus on the mutual effects between such perceptions and the feedback provided by our system.

9 Conclusion

The Imaginary Joint system is an interface that provides proprioceptive feedback for extended virtual body parts in VR. By positioning an Imaginary Joint at the interface between the innate and extended body, the system can present the fictional sensation that "if such a body part existed, this is how it would feel", through localized skin-stretch around the joint. The system aims to provide feedback that feels more natural (i.e. innate-body like) and intuitive than conventional vibrotactile signals, conveying both the extension's angle and the torque it produces.

In summary, the proposed skin-stretch feedback based on the Imaginary Joint approach succeeded in conveying the virtual tail's angle and torque more effectively than vibrotactile feedback. Furthermore, subjective evaluations indicated a superior user experience: participants reported a stronger sense of embodiment, greater enjoyment, and a more natural and intuitive perception of the tail's sensations. These results suggest that a system that delivers information through modalities resembling the innate body, rather than merely transmitting data from extended body parts, has the potential to contribute to high-quality user experiences and improved performance.

In conclusion, the Imaginary Joint system enables "body-like" feedback from extended body parts, thereby enhancing both their perception and embodiment. Because this feedback system is designed independently of the control methods, it can be applied across a wide range of scenarios. In particular, it offers significant benefits over existing feedback systems in applications where multiple factors—such as embodiment, motor performance, and the naturalness of sensation—are critical, including extended-body perception, bodily expression with extended bodies, and body-mediated communication. In doing so, it brings us closer to truly feeling extended bodies as part of ourselves.

Acknowledgments

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