Imaginary Joints and Muscles: Torque-based Proprioceptive Illusions for Extended Body Parts via Skin Stretch Feedback

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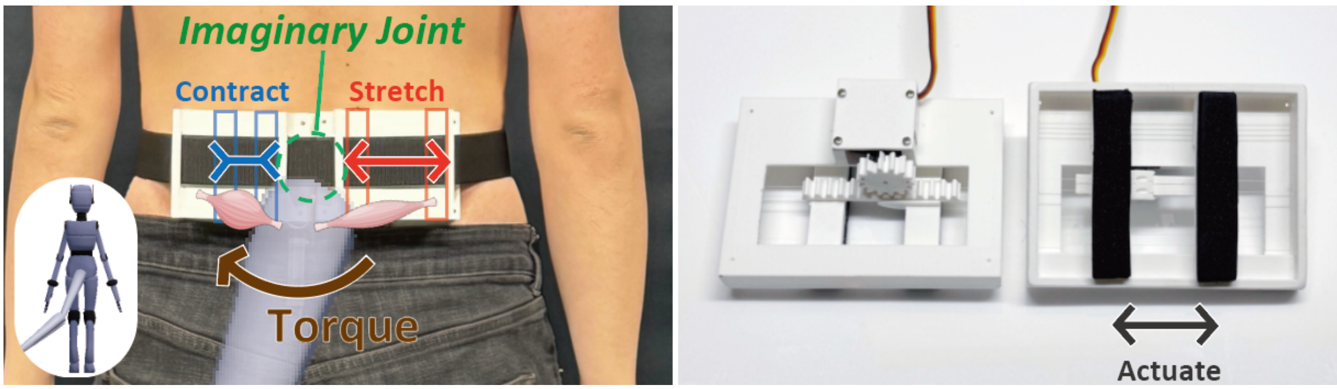

Figure 1: "Imaginary Joints and Muscles" Concept Illustration. Our system renders muscle-like sensations at the connection point of a virtual extended body part. (Left) The user receives skin-stretch feedback from the "Imaginary Joint" of a virtual tail. (Right) Two skin-stretch devices simulate "Imaginary Muscles" sensations on both sides of a 1-DOF joint, stretching the skin according to the torque that the root joint is supposed to generate.

Abstract

Extended body parts such as a third arm or tail have the potential to offer users new bodily experiences and capabilities. In this paper, we propose a method to enable users to intuitively perceive the posture and motion of such extended body parts without relying on vision, by introducing the concept of "Imaginary Joints and Muscles". Our approach provides proprioceptive feedback based on torque information via skin stretch. Specifically, we place an "Imaginary Joint" at the interface between the user's body and the extended body part, and the skin around the joint is stretched or compressed in accordance with the motion of the extended body. This allows the user to recognize the movement, in a modality close to innate proprioceptive sensation. The system calculates the torque required for the movement of the extended part and feeds it back to the user, making it applicable to a wide range of scenarios—including physics-based simulations, animations, externally induced movements and mapped manipulations. Through our demonstration, we show that multiple extended parts and various scenarios can be intuitively felt, highlighting the broad potential and versatility of our approach.

CCS Concepts

• **Software and its engineering** → **Interactive games**; • **Human-centered computing** → **Haptic devices**; **Virtual reality**.

Keywords

human augmentation, avatar, XR, proprioceptive feedback

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1 Introduction

In recent years, "extended body" technologies that add extra limbs, fingers, or tails have gained attention for their potential to enhance human capabilities, support tasks, and enrich experiences in fields such as rehabilitation, industry, and VR/AR. By introducing new bodily functions—like a third arm[Saraiji et al. 2018]—these technologies can complement lost functions, improve multitasking, and expand creative expression.

A key challenge is to provide natural proprioceptive feedback so that users can sense the posture and movement of these artificial parts as if they were innate, rather than relying solely on visual cues. Previous research has used vibration to convey the position of an end-effector[Iwasaki et al. 2020], but this modality differs substantially from the authentic sensation of proprioception. While neural electrical stimulation[Wendelken et al. 2017] can leverage existing nerve pathways for prosthetic applications, it is less suitable for body parts that did not originally exist.

In this paper, we introduce a system that creates an "Imaginary Joint" at the interface between the user and an extended limb, using skin-stretch to simulate torque and evoke a sense of "Imaginary Muscles." This system is inspired by previous research on using skin-stretch feedback in residual limbs to convey prosthetic posture sense[Trujillo-Trujillo et al. 2022]. By calculating the forces required for each motion and delivering them through skin-stretch, users can perceive the posture and movement of the extended limb more naturally, thereby reducing reliance on vision. Our demonstration highlights the broad applicability of this approach, promising more intuitive and immersive experiences in extended body scenarios.

2 Torque-to-Skin Stretch

This system calculates the torque that should be generated at the root of the extended body part, based on the part's motion, and conveys that torque to the user as skin stretch. We consider two operational modes—*passive* and *active*—to accommodate a range of scenarios in which the virtual body part might move. The final torque value is mapped via a nonlinear, monotonically increasing function that accounts for the user's sensitivity to skin stretch.

2.1 Passive Mode

This mode assumes the user allows the extended part to move passively, such as a tail swaying in response to hip movement. We approximate the motion using a spring-damper system, in which vibrations converge over time. Let θ be the angular deviation from the equilibrium position, and let k and b be proportional constants. The base-exerting torque T is given by:

$$T = -k\theta - b\dot{\theta}. \tag{1}$$

Even though inertial terms like mass M or moment of inertia I do not explicitly appear in this formula, the time-series changes in T reflect the weight of the extended part. When the extended body is displaced by external forces (e.g., collisions or other users' interactions), we do not precisely calculate all external torques; rather, we provide the user with a restoring force that aims to return the extension to its initial position.

2.2 Active Mode

This mode is used when the user actively controls the extended part—for instance, when it is holding or manipulating an object using a motion mapping, or when a predefined animation is driving the motion. Here, we consider the moment of inertia I of the part. Let T_{outer} represent external torques, such as those from an object in the extended part's grasp. The torque T is given by:

$$T = I\ddot{\theta} - T_{\text{outer}}. \tag{2}$$

By calculating the final torque for each motion and feeding it back through skin stretch, the user feels a muscle-like sensation corresponding to both internal forces and external interactions.

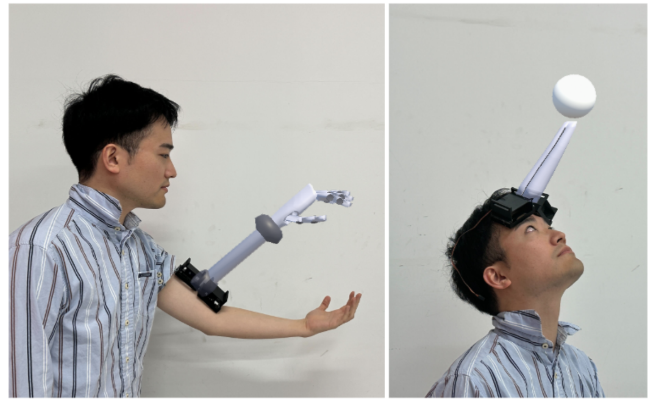

Figure 2: This feedback system can be applied to almost any area of the user's skin. (Left) An additional arm extends from the user's upper arm. (Right) The user bounces a sphere off an hone, experiencing a torque at the moment of collision. In these examples, a smaller version of the device is used.

3 User Experience

Unlike other approaches, this system can be broadly applied to almost any region of the user's body where skin is present. The "Imaginary Joint" metaphor works with any control scheme and integrates seamlessly with physics simulations, keyframe animations, and mapping-based control of extended limbs. By using this metaphor instead of mere informational feedback, it gives users more intuitive, natural sensations of movement. In our demonstration, users actively or passively manipulate a third arm, a tail, or wings, experiencing these motions through imaginary proprioceptive cues. Notably, even with their eyes closed, users can perceive the approximate exerting force and position of the extension, suggesting the potential for more intuitive interactions and reduced reliance on visual feedback.

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References

Yukiko Iwasaki, Kozo Ando, Shuhei Iizuka, Michiteru Kitazaki, and Hiroyasu Iwata. 2020. Detachable Body: The Impact of Binocular Disparity and Vibrotactile Feedback in Co-Presence Tasks. *IEEE Robotics and Automation Letters* 5, 2 (2020), 3477–3484. doi:10.1109/LRA.2020.2977320

MHD Yamen Saraiji, Tomoya Sasaki, Kai Kunze, Kouta Minamizawa, and Masahiko Inami. 2018. MetaArms: Body Remapping Using Feet-Controlled Artificial Arms. In *Proc. of UIST 2018* (Berlin, Germany). 65–74. doi:10.1145/3242587.3242665

Emir Trujillo-Trujillo, Kevin Acuna-Condori, and Marina Gabriela S. P. Paredes. 2022. Evaluation of the Skin Fixation Method of a Haptic Device to Provide Proprioceptive Information for a Sensory Feedback Prosthesis. In *2022 IEEE ANDESCON*. 1–6. doi:10.1109/ANDESCON56260.2022.9989931

Suzanne Wendelken, David M. Page, Tyler Davis, H. A. Christie Wark, Daniel T. Kluger, Cody Duncan, Derek J. Warren, David T. Hutchinson, and Gregory A. Clark. 2017. Restoration of motor control and proprioceptive and cutaneous sensation in humans with prior upper-limb amputation via multiple Utah Slanted Electrode Arrays (USEAs) implanted in residual peripheral arm nerves. *Journal of NeuroEngineering and Rehabilitation* 14, 1 (Nov 25 2017), 121. doi:10.1186/s12984-017-0320-4