Move with Style! Enhancing Avatar Embodiment in Virtual Reality through Proprioceptive Motion Feedback

David Wagmann*
Saarland University,
Saarland Informatics Campus
Saarbrücken, Germany
wagmann@cs.uni-saarland.de

Marie Muehlhaus*
Saarland University,
Saarland Informatics Campus
Saarbrücken, Germany
muehlhaus@cs.uni-saarland.de

Jürgen Steimle
Saarland University,
Saarland Informatics Campus
Saarbrücken, Germany
steimle@cs.uni-saarland.de

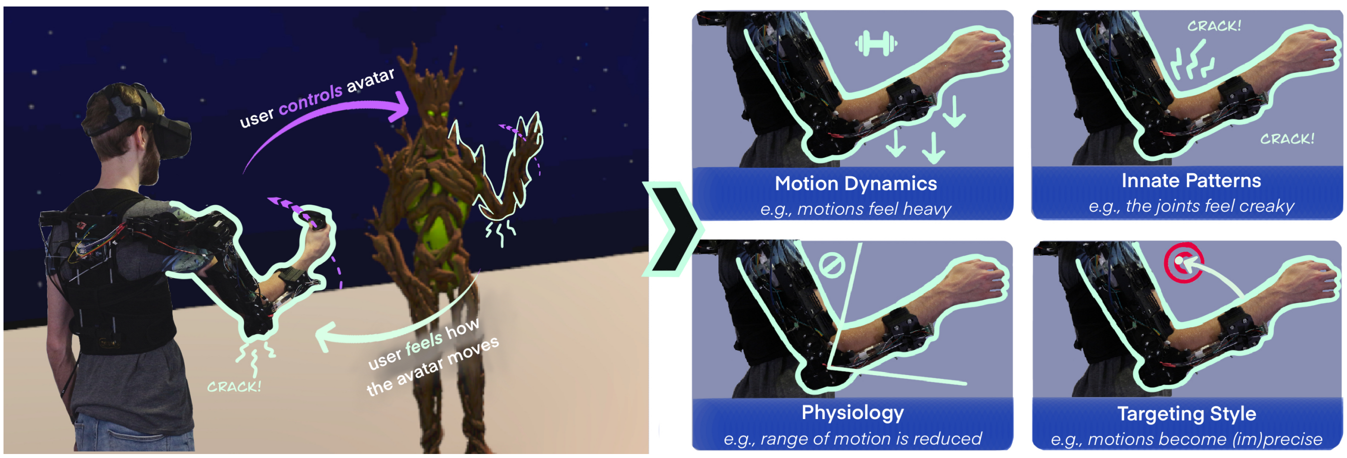

Figure 1: We propose proprioceptive motion feedback to align user's physical movements with the expected motion style of their avatar to enhance embodiment in virtual reality (VR). *MotionStyler* is a proof-of-concept system for designing and rendering such proprioceptive motion styles in real-time in VR with an arm-based exoskeleton. Based on a conceptual space comprising eight motion properties grouped into four key dimensions, an accompanying design tool helps designers to combine individual properties into expressive proprioceptive motion styles; e.g., they might mimic the motion style of a rigid treefolk by combining the sensation of heavy, creaky limbs with a reduced motion speed and range.

ABSTRACT

In virtual reality (VR), users slip into a variety of roles, represented by a rich diversity of avatars that each exhibit specific visual attributes and motion styles. While users can see their avatar's motion in VR, they usually cannot *feel* it. To enhance avatar embodiment, we propose active proprioceptive feedback that aligns users' physical movements with the expected motion style of their avatar, for instance, by mimicking the avatar's weight, typical motion speed or motion range. We introduce a conceptual space of relevant motion properties which enable designers to create expressive proprioceptive motion styles for avatars. We instantiate this concept with *MotionStyler*: a system for designing customized motion styles and rendering them in real-time with an arm-based exoskeleton that is synchronized with the VR avatar. Results from a survey confirmed the expressiveness of the proposed conceptual space. A user study demonstrated the system's capability to create diverse proprioceptive motion styles which enhance user's self-identification with their avatar and thereby positively contribute to avatar embodiment in VR.

CCS CONCEPTS

• **Human-centered computing** → **Interactive systems and tools**.

KEYWORDS

Virtual reality; avatar; embodiment; motion style; augmented human; proprioception.

*These authors contributed equally to this research.

UIST '25, September 28-October 1, 2025, Busan, Republic of Korea

ACM ISBN 979-8-4007-2037-6/2025/09.
https://doi.org/10.1145/3746059.3747649

ACM Reference Format:
David Wagmann, Marie Muehlhaus, and Jürgen Steimle. 2025. Move with Style! Enhancing Avatar Embodiment in Virtual Reality through Proprioceptive Motion Feedback. In *The 38th Annual ACM Symposium on User Interface Software and Technology (UIST '25), September 28-October 1, 2025, Busan, Republic of Korea.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3746059.3747649

1 INTRODUCTION

Research on avatars in VR (e.g., [13, 30, 42, 64, 69]) has gained increasing interest in the HCI community as they allow users to slip into a variety of roles. A key challenge lies in fostering a sense of embodiment (SoE) – the impression of being the virtual avatar – as this positively affects user experience [22], performance [38], and perceived realism [23]. One promising means to fostering this SoE is to establish a sensory relationship between the user and the avatar, ensuring that perceived and expected sensory feedback align [45]. So far, prior work especially demonstrated the positive effects of aligning visual and tactile sensory feedback [14, 41, 43].

In contrast, only few works considered how to establish a proprioceptive relation between user and avatar. This seems critical as prior work noted that matching visual, tactile, and proprioceptive stimulation can positively contribute to the user's sense of owning and controlling the avatar's body [32]. Hence, we argue that it is also important for the user to not only see, but also to *feel* their avatar's motion in VR. For example, when embodying a heavy giant, users should feel a greater sense of gravity in their limbs, whereas when embodying an elf, associated with elegant and fluid movements, users should feel a sense of weightlessness. However, establishing such a proprioceptive relationship remains challenging to realize. First, humanoid VR avatars can exhibit diverse motion styles, and we lack a systematic understanding of the motion properties required to effectively shape the proprioceptive experience. Second, existing approaches often focus on isolated properties (e.g., [35, 43]), do not target the feedback to the individual body part but rather use hand-held proxies [35], or rely on illusions that may be prone to breaking [8, 36, 42]. Here, the challenge lies in developing a system that can effectively combine several motion properties into expressive and diverse proprioceptive motion styles.

In this paper, we propose active proprioceptive feedback that aligns users' physical movements with the expected motion style of their avatar in order to enhance avatar embodiment in VR (see Figure 1). First, we introduce a conceptual space of distinct motion properties that shape the user's proprioceptive experience when embodying their avatar. These properties can then be systematically combined into expressive and diverse avatar motion styles. We instantiate this concept with *MotionStyler*, a proof-of-concept system that enables designers to create and experience proprioceptive motion styles for humanoid avatars. *MotionStyler* consists of a tool for composing customized motion styles, an arm-based exoskeleton that renders the corresponding proprioceptive feedback in real-time, and a VR environment for experiencing the designed motion styles in an immersive setting.

We first identified a set of relevant motion properties through a two-fold approach which combines systematic and empirical methods, and clustered these properties into four key dimensions: (1) *motion dynamics* describe the weight of the avatar's body and the avatar's characteristic motion speed and acceleration patterns, (2) *innate patterns* specify avatar-specific behaviors, ranging from intermittent motions, such as stuttering, to fully narrated motions, such as pre-defined motions in VR cutscenes, (3) *physiology* captures the avatar's limitations in its range of motion, and (4) the *targeting style* describes the precision and trajectory with which the avatar typically approaches a target.

MotionStyler's design tool enables designers to combine these motion properties into complex proprioceptive motion styles. To support both novices and experts, the design tool offers presets for rapid explorations as well as fine-grained control over the individual motion properties. The connected arm-based exoskeleton renders the designed motion style in real-time.

We validated the proposed concept with two user studies. First, we conducted an online survey (N=19) in which participants characterized the motion styles of 12 distinct avatars based on the four dimensions of our conceptual space. The results demonstrate that the conceptual space is able to capture the distinct motion styles of diverse humanoid avatars and helps to identify salient motion properties. Second, we conducted a lab study (N=12) to evaluate *MotionStyler* and the effects of aligning user's physical movement with the expected motion style of their avatar. The results confirm that *MotionStyler* supports a creative exploration and customization of motion styles. Furthermore, we found that proprioceptive motion styles can enhance self-identification with the avatar and that participants tend to adapt their motion to the avatar's motion style if the proprioceptive feedback aligned with their expectations. Notably, while proprioceptive feedback slightly reduced perceived agency, participants found this acceptable or even desirable when it matched with the expected motion capabilities of the avatar.

In summary, this paper contributes:

(1) A conceptual space of essential motion properties that can be combined into expressive motion styles for avatars in VR, serving to establish a proprioceptive relationship between a user's physical movements and the expected motion style of their avatar.
(2) *MotionStyler*, a proof-of-concept system for creating, rendering, and experiencing avatar motion styles in real-time in VR with an arm-based exoskeleton.
(3) Findings from a survey which validates the descriptive power of the conceptual space and a study which demonstrates the utility of *MotionStyler* and the potential of proprioceptive motion styles to enhance avatar embodiment in VR.

2 RELATED WORK

This work is informed by prior work on avatar embodiment in VR, movement analysis, and proprioceptive feedback devices in HCI.

2.1 Avatar Embodiment in VR

The sense of embodiment emerges from three key components: a user's self-attribution to a virtual avatar (termed body ownership or bodily self-identification [32]), the sense of having control over the virtual body (agency) and the sense of being located inside the virtual body (self-location) [23]. Enhancing the SoE can positively affect user experience [22], performance [38], perceived realism [23] and even elicit behavioral and perceptual changes [72]. These benefits make avatar embodiment relevant for various VR applications such as for therapy [67, 71], gaming and social applications (e.g., VRChat[1], Metaverse[2]). Prior work argued about the importance to align user expectations with the perceived sensory

[1]VRChat: https://hello.vrchat.com, last accessed 7/14/2025
[2]Metaverse: https://about.meta.com/en/metaverse/, last accessed 7/14/2025

feedback [45] as matching visual, tactile, and proprioceptive stimulation can positively influence agency and bodily self-identification with a body [32]. The Rubber Hand Illusion is one prominent example that demonstrates how multisensory feedback can enhance the bodily self-identification with foreign body parts [7]. Similarly, related work has shown that the subjective experience of embodying a robot in VR can be enhanced through a combination of visual, tactile and auditory feedback, where the latter two modalities serve to mimic the creaking experience of a moving robotic joint [43]. However, only few works have considered the importance of proprioceptive feedback so far: For example, inspired by [43], PneumAct applies proprioceptive perturbations to make the user's arm movements less fluid, creating robotic-like motion sensations [26]; others used an exoskeleton providing resistance to the user's arms to mimic air resistance or a back-wearable device providing on-body weight-shifts to embody wings [9, 54] or alter the weight perception of avatars in VR with the help of a wearable force feedback device [27], a handheld device which gains or loses weight [35] or through illusions [36]. Of note, existing work has primarily targeted isolated properties such as weight perception, whereas body perception usually involves complex interactions of multiple properties, which in turn constitute a unique proprioceptive motion style. Our work aims to address this gap by exploring essential motion properties and how these properties can be combined into expressive proprioceptive motion feedback that represents an avatar's unique way of moving, thereby enhancing avatar embodiment in VR.

2.2 Understanding Motion Styles

To realize proprioceptive motion styles, it is essential to understand what defines a motion style. One widely used theoretical framework for analyzing and describing motion is the Laban Movement Analysis (LMA) [18]. It characterizes human motion through four effort factors described as polar qualities:

- *Time* refers to the timing of the movement which can either be sustained or sudden. Sustained movement is ongoing and does not exhibit drastic changes in velocity, while a more sudden movement is characterized by quick changes in the body movement, such as flinching when frightened.
- *Weight* describes how gravity impacts the body, but also the energy or powerfulness of a motion. It ranges from light to strong movements, such as grabbing a cup forcefully or delicately.
- *Space* describes the focus of our body and our spatial orientation. It can either be direct, associated with straight movements, or indirect, meaning that we are more flexible with the use of orientation and space.
- *Flow* describes the progression or transitions of movements, which can be either bound or free.

These efforts have been applied across disciplines, including performative arts [47, 53], animation [6], and robotics [1, 46, 52]. For instance, prior work leveraged LMA to replicate ballet character movements in a NAO robot [2], explore stylistic variations in robotic motion [46], and express emotions through movement [50]. Despite its expressive power, LMA remains qualitative and there exist diverse approaches to translate the efforts into computational properties [40]. Furthermore, the LMA may not yet adequately capture all the properties needed to design and render the variety of VR avatar motion styles with a proprioceptive feedback device. Therefore, this work builds on and extends the LMA to identify essential properties that allow us to systematically express and design proprioceptive motion styles suitable for avatars in VR.

2.3 Proprioceptive Feedback Devices

In previous work, a variety of devices have been developed to provide proprioceptive feedback. These include, for instance, grounded devices [11], handheld proxies [29, 31, 35] and wearables [25, 48, 56]. Our work focuses on wearable devices that provide proprioceptive feedback directly to the body. Two common methods are electrical muscle stimulation (EMS) and exoskeletons: EMS triggers muscle contractions via electrical impulses. In the HCI community, EMS is a frequently used method to adjust or even enforce movements [28, 60, 65] and provide various proprioceptive feedback in VR [37, 49, 61]. However, while toolkits facilitate the usage of EMS [59], its time-consuming calibration and limited precision of actuation [39] make EMS less suitable for this work, which aims to render diverse and customizable motion styles. In contrast, exoskeletons offer a more versatile approach by physically augmenting motions through applied forces. Prior work demonstrates their versatile potential for HCI, such as for motion learning [51, 58], gaming and VR [25, 54, 66]. Exoskeletons can augment user motions in various ways; for instance, they can provide tactile or proprioceptive notifications, modify a user's motion speed, or ease the user's motion effort [54]. The diverse and accurately controllable ways in which an exoskeleton can modify a user motion make this technology a particularly promising solution for our work.

3 MOTION STYLE PROPERTIES

The aim of this work is to enhance avatar embodiment in VR by aligning the user's physical movements with the expected motion style of their avatar. To achieve this, we propose to use proprioceptive feedback that allows the user to *feel* the motion style of their virtual avatar while controlling its movements (see Figure 1). Since a motion style is usually the result of an interplay between several individual motion properties, we first set out to identify a set of salient and distinct motion properties that are relevant when embodying humanoid avatars in VR. The resulting motion properties can then be combined and therefore serve as a conceptual foundation for designing proprioceptive motion styles for avatars.

3.1 Approach

To identify a set of salient properties, we employed a two-fold approach that combines systematic and empirical methods (cf., Table 1): First, we systematically derived an initial set of properties from the efforts of the Laban Movement Analysis model (LMA), a widely used framework for motion style analysis (cf., subsection 2.2). As the LMA primarily describes movement qualitatively, we translated the weight, time, and space efforts into five concrete properties (*weight*, *speed*, *acceleration*, *precision*, *trajectory*) that can be operationalized in a proprioceptive device. As we do not consider the sequencing of motions but identify distinct properties which are provided as continuous proprioceptive feedback, we excluded Laban's flow effort from the analysis. Next, we extended this initial set with three additional properties (*range of motion constraint*,

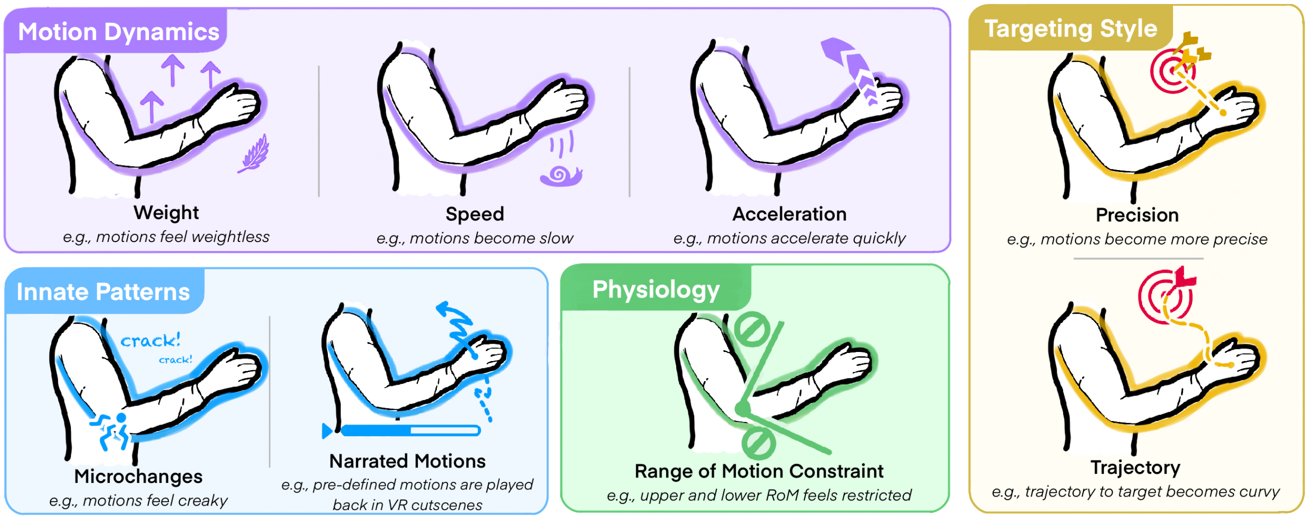

Figure 2: The conceptual space of motion properties comprises four key dimensions: motion dynamics, innate patterns, physiology, and targeting style. The individual motion properties can be combined into expressive motion styles.

microchanges, *narrated motions*) tailored to the special demands of avatars in VR. These properties were derived through an empirical investigation of existing research (e.g., [24, 35, 37, 43]), movement characteristics of humanoid avatar species from popular fantasy and science-fiction books[3][4] and role-playing games[5][6], and iterative discussions among co-authors. We specifically also included fictional humanoid avatar species because they may have significant physiological differences from human avatars, resulting in distinct motions styles which our conceptual space should be able to capture. Finally, we clustered the identified properties into four key dimensions, forming our conceptual space (see Figure 2). We introduce the dimensions in the following:

3.2 Motion Dynamics

Motion dynamics encompass the avatar's body weight and the avatar's characteristic motion speed and acceleration patterns. Building on insights from prior work [40, 44], we derived weight, which affects how effortful or light a motion feels, from Laban's weight effort (= forceful to delicate motions), and velocity and acceleration from Laban's time effort because these two properties together characterize how sustained or sudden a movement is [4, 62]. Due to the close physical relationship between weight, acceleration, and speed, they together describe the dynamics of an avatar's motion. We next discuss the relevance of these motion properties for VR avatars and how they can be realized with a proprioceptive feedback device:

Weight. Weight modulates whether the user's movements feel light or heavy and is a motion property that was frequently considered in prior work (e.g., [27, 35, 36]). Weight depends on the avatar's physical characteristics and is affected by the magnitude of gravitational force impacting the body [20]. For example, a rock giant with massive, heavy limbs may experience a strong gravitational pull, whereas the limbs of a filigree elf may feel nearly weightless. With a proprioceptive device such as an exoskeleton, we can alter the perceived weight by altering the impact of gravitation: We can create a sensation of high gravity, i.e., heavy limbs, by applying downward-directed forces to the user's arms. Conversely, upward-directed forces create a sense of weightlessness. To tailor this property to different avatars, our design tool gives designers control over the magnitude and direction of the applied force, where higher values result in stronger effects.

Speed. The speed property describes the ability to regulate a user's motion speed to align with an avatar's expected movement capabilities. This is important as different avatars can be associated with different movement speeds. For instance, a teddy bear may be associated with slow motions, while a robot may be capable of moving with higher speed. However, only few works have investigated this property so far (e.g., [36]). In order to establish a proprioceptive relationship and prevent the user from moving at an inappropriate speed, the exoskeleton must be able to limit the user's speed accordingly. This can be achieved by applying resistance when the user's movement exceeds the avatar's predefined speed threshold to slow them down, while slower movements remain unaffected. Here, designers must have control over the threshold and the intensity with which the exoskeleton reacts to changes in motion speed.

Acceleration. Acceleration complements the speed property and modifies how a user's motion accelerates and decelerates, thereby influencing how sustained or sudden the motions feel. For example, to align the user movements with a robot that tends to maintain a steady velocity with quick but steady accelerations or a lizard-like avatar which exhibits abrupt bursts of motion, the proprioceptive system must be able to modify a user's acceleration and

[3]Best Selling Fantasy Books: https://wordsrated.com/fantasy-book-sales-statistics/, last accessed 7/14/2025
[4]Best Selling Sci-Fi Books: https://wordsrated.com/science-fiction-book-sales-statistics/, last accessed 7/14/2025
[5]Dungeons And Dragons: 10 Most Popular Races To Play As: https://screenrant.com/dungeons-and-dragons-most-popular-races-dnd/, last accessed 7/14/2025
[6]Baldur's Gate 3 Races: https://bg3.wiki/wiki/Races, last accessed 7/14/2025

Dimensions	Properties	Laban Effort	Example Works	Avatar *[Trait]* Examples
Motion Dynamics	*Weight*	Weight	[20, 27, 35, 36]	Elf *[Light]* vs. Giant *[Heavy]*
	Speed	Time	[36]	Teddy *[Slow]* vs. Robot *[Fast]*
	Acceleration	Time	✗	Robot *[Constant]* vs. Lizardfolk *[Sudden]*
Innate Patterns	*Microchanges*	✗	[43]	Robot *[Mechanical stuttering]* or Lizardfolk *[Twitching]*
	Narrated Motions	✗	[16, 37]	Teddy *[Joyful swinging]* or Robot *[Static default pose]*
Physiology	*Range of Motion*	✗	[24, 54]	Elf *[Unconstrained]* or Treefolk *[Stiff]*
Targeting Styles	*Precision*	Space	[74]	Rock giant *[Imprecise]* vs. Robot *[Precise]*
	Trajectory	Space	[44, 68]	Rock giant *[Curved]* vs. Robot *[Straight]*

Table 1: The table provides an overview of the related Laban efforts, example prior work and avatar traits that informed the selection of the four dimensions and their motion style properties.

deceleration profiles accordingly. This can be achieved by applying forces which either restrict or enforce rapid accelerations and decelerations. To support designers in rapidly trying out different behaviors, users can select between pre-implemented constant or linear acceleration and deceleration profiles in our design tool.

3.3 Innate Movement Patterns

While the properties of the motion dynamics dimension react primarily to the user's inherent motions, avatars can also exhibit specific innate behaviors that (re-)occur at certain times or time intervals without active involvement of the user. We have empirically derived two types of innate movement patterns from analyzing avatar motion characteristics and prior work (e.g., [16, 37, 43]):

Microchanges. Microchanges describe brief, intermittent motions that are layered onto a user's inherent movement. Unlike properties such as weight, which continuously affect motion, microchanges introduce discrete perturbations. The relevance of this property is rooted in the observation that certain avatars exhibit innate involuntary motions that interleave with intentional user movements. For example, a rusty robot might exhibit small and frequent mechanical stutters, while an avatar like the lizardfolk might experience sporadic twitches. A similar concept has been suggested in prior work, where innate vibrations from real robot actuation were recorded and replayed onto a user's body motion [43]. To design such microchanges, we must allow designers to define repeating motion patterns that the proprioceptive system can lay over user movements while preserving overall control. The tool enables users to specify the microchanges either manually by defining time-series data or by recording the intended microchange through demonstration. Additional control parameters allow to adjust the scale and speed at which the defined microchange is played back and a minimum and maximum interval between occurrences of microchanges to regulate the randomness.

Narrated motions. Narrated motions are pre-defined sequences of motions that are played back on the user's body. In contrast to microchanges, a narrated motion is played continuously instead of intermittently. This property is based on insights from prior work which (1) has shown that proprioceptive feedback can enhance the experience of in-game cutscenes, which are non-interactive scenes in which the system temporarily takes over control [37] and (2) has argued that avatars do not necessarily remain static during the absence of deliberate user actions. Instead, they can exhibit distinct postures or movement patterns, termed idle motions [16]. For instance, a joyful teddy might keep swinging its arm, while a robot returns to a static default pose in its idle state. A key challenge for these narrated motions, in contrast to other motion properties, is that they temporarily take full control over the user's body, as the proprioceptive device actively moves the body through a pre-defined motion sequence. Hence, to preserve user safety and agency, narrated motions must remain cancelable. As with microchanges, our design tool enables designers to create narrated motions either by manually specifying a time-series of movements or through a record-and-replay mechanism, and fine-tune the speed and scale. Furthermore, the system allows users to break out of a narrated motion if a specified force threshold is exceeded, which ensures that users can regain control when needed.

3.4 Physiology

Another important factor when embodying a humanoid avatar is to align the avatar's and user's physiological characteristics. This is to prevent the user from performing motions that would be impossible for the avatar, potentially breaking the experience of proprioceptive alignment. Since our focus is on humanoid avatars, i.e., avatars that have the same overall joint structure as the person embodying the avatar, we have empirically identified the range of motion as a particularly salient property that affects motion style:

Range of motion constraint. The range of motion (RoM) is a key property in the biomechanics of the human upper limbs [54] and defines the maximal angular movement of a joint. Enforcing an avatar-specific RoM prevents users from performing anatomically impossible movements, thereby enhancing the proprioceptive relationship. For instance, while an elf's range of motion might be similar to that of a human, a stiff treefolk avatar might only be able to bend its arms to a much smaller degree. However, only

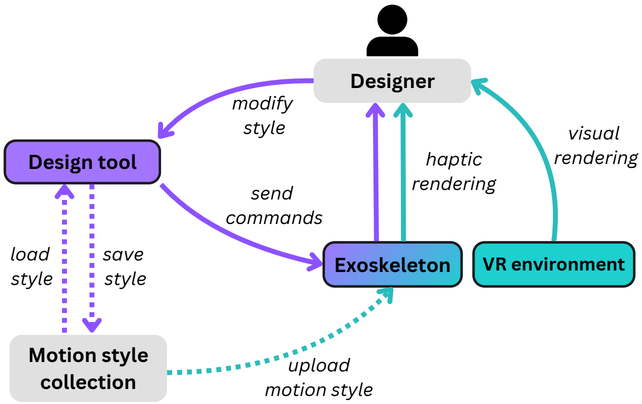

Figure 3: *MotionStyler* allows users to create custom motion styles, which are rendered in real-time with an arm-based exoskeleton. The designed motion style can then be experienced with matching visual feedback in a VR environment.

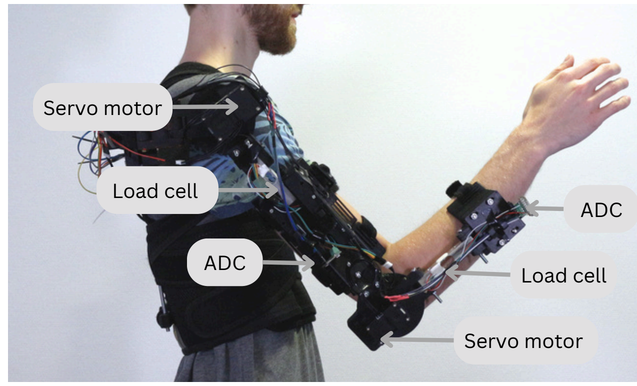

Figure 4: We use an arm-based exoskeleton with 2 active degrees-of-freedom at the shoulder and elbow to render the proprioceptive motion styles.

few works have investigated how altering the RoM affects avatar embodiment so far. One example is the work by Granqvist et al., who leveraged illusions to increase the perceived flexibility of a VR avatar [24]. Proprioceptive devices like exoskeletons, however, enable the inverse, as they can physically restrict a user's RoM to match an avatar with a smaller RoM. To constrain the user's RoM, an exoskeleton can resist user movement when the user tries to leave the specified RoM. Within the permitted RoM, the user can move freely. The design tool allows designers to specify the upper and lower limits of each joint's range of motion to define physiological constraints that match the desired avatar.

3.5 Targeting Style

An important interaction in VR is grabbing or manipulating objects. Based on Laban's space effort (= direct to indirect motions) and interpretations of this effort in previous works [40, 44], we derived the two properties precision and trajectory as a means to describe an avatar's targeting style. We argue that precision and trajectory are two essential properties to describe the targeting style of an avatar as the way an avatar approaches a target object can convey key aspects of its character–for instance, a rock giant with massive limbs might have less fine-grained motor control, making it difficult to move in straight trajectories or to precisely stop at an intended target position, whereas a robot is usually designed to move with high precision and straight trajectories. We detail on these two properties in the following:

Precision. Precision determines how accurately an avatar is able to reach a targeted position in space. Conceptually, this closely relates to approaches in prior work, which utilized hand redirection techniques in VR to shift the user's real-world target position [74]. Conversely, we can use a proprioceptive device to modify the virtual target position by physically displacing the real hand: If the exoskeleton pushes the user's hand slightly beyond the targeted object, we can realize an imprecise targeting style, while for a precise targeting style, the exoskeleton must ensure that the user stops exactly at the intended target position. In the design tool, the designer can control the degree of (im)precision by defining the minimum and maximum distance from the targeted position at which the exoskeleton would stop the user. A greater distance to the target leads to greater imprecision, a smaller distance to greater precision. Additionally, a designer must regulate the intensity of the corrective forces, the dwell time at which the user is held at the target position, and the distance from the target at which the exoskeleton starts to influence the movement precision. Increasing these values gives the device more control over the user, whereas a lower value minimizes interference with the user's inherent motions.

Trajectory. Trajectory defines the path an avatar's movement follows when reaching for an object. As reaching motions can exhibit an extensive range of possible trajectories [68], we argue that these trajectories may also vary across different avatar species, raising the need for unique targeting trajectory styles. An exoskeleton can modify the user's trajectory by applying corrective forces. For instance, these forces can smoothen out irregularities, enforce a straight-line trajectory, or introduce curves. Hence, it is essential to provide designers with control over how the trajectory is altered. The design tool offers two pre-implemented trajectory modes: one that enforces a direct, linear motion towards a target position and one for curved motions.

In the next section, we detail on how these motion properties can be implemented and combined into expressive motion styles.

4 MOTIONSTYLER

MotionStyler is a proof-of-concept system which enables designers to create and experience proprioceptive motion styles. It comprises three parts (see Figure 3): With the help of a design tool, designers can compose individual motion properties into customized motion styles or fine-tune existing proprioceptive motion styles. The design tool is connected to an arm-based exoskeleton, which renders the proprioceptive motion styles in real-time. Once satisfied with the design, the proprioceptive motion style can be saved and experienced in combination with the respective visual avatar in VR. In the following, we provide details on the individual components, starting with the haptic rendering system as the central component.

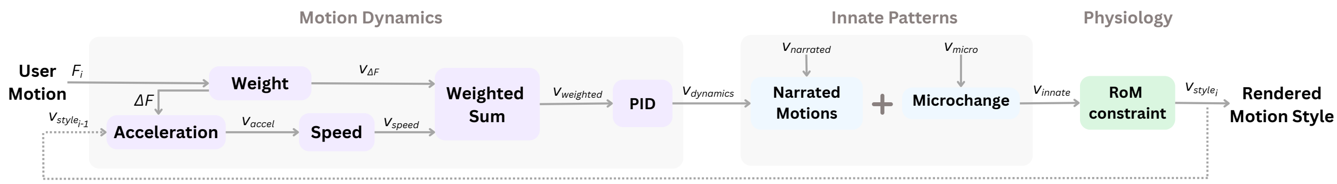

Figure 5: To render the proprioceptive motion style, the system calculates the goal velocity v_{style} at loop execution time i, which is then executed by the exoskeleton's motors. Based on the force F_i applied by the user and the target velocity v_{style} from the previous loop execution $i-1$, we first calculate the effect of the motion dynamics on the goal velocity, followed by the innate patterns and physiology. This gives the new goal velocity v_{style}.

4.1 Haptic Rendering System

4.1.1 Exoskeleton. We prototypically implement the motion styles in an arm-based exoskeleton (see Figure 4). The exoskeleton prototype was built with ExoKit [54]. It has two active degrees-of-freedom (DoF) that augment flexion-and-extension movements at the shoulder and elbow. An additional passive DoF in the shoulder enables users to perform abduction-adduction movements. We use a Dynamixel XM540-W270-T servo motor at the shoulder and a Dynamixel XM430-W210-T at the elbow. The system requires one load cell per actuated joint. Thus, a total of two load cells, each with an HX711 24-bit Analog-to-Digital Converter (ADC), are attached at the lower and upper arm segments to capture interaction forces. The motors interface with the Dynamixel Shield for Arduino, while an Arduino Mega manages the communication with the motors and sensors.

4.1.2 Motion Control. The system comprises separate algorithms that calculate the effect of each motion property and a main loop that combines them into a final motion style. The algorithms were developed with C++ in platformIO. The software communicates with the exoskeleton through a serial port and manages the low-level motion control. To control the motors, we chose a velocity control mode, as this modifies the user's motions more smoothly [73]. Consequently, each algorithm outputs a goal velocity v at loop execution i. These velocities are combined into the final goal velocity v_{style_i}, which renders the desired motion style at loop execution i (see Figure 5). The system generally processes the readings from each load cell and the calculated velocities independently for each joint, enabling designers to freely choose which joint to (de)activate during runtime. The only exception is targeting styles, where the sensor readings are combined, as reaching for a target point requires effective coordination of goal velocities between all active joints. We present the algorithms in the following:

Altering the motion dynamics. To alter the **weight** perception, we first calculate the force difference $\triangle F$ between the user's exerted force F_i, adjusted by the load cell's calibrated zero force reference F_0, and the targeted gravitational force F_{weight} for each joint:

$$\triangle F = F_i - F_0 - F_{weight}$$

We then use $\triangle F$ to determine the direction in which the user tries to move. If the intended movement direction is the same as the system's current movement direction, then the velocity $v_{style_{i-1}}$ is modified based on the user-defined **acceleration** curve $accel(\cdot)$ (if any) as:

$$v_{accel} = v_{style_{i-1}} + accel(v_{style_{i-1}})$$

Otherwise, the deceleration curve $decel(\cdot)$ analogously determines the velocity loss as $v_{accel} = v_{style_{i-1}} - decel(v_{style_{i-1}})$. *MotionStyler* allows users to choose between no, constant, or linear acceleration and deceleration curves. Finally, we limit the output velocity based on the user-defined **speed** threshold:

$$v_{speed} = \frac{|v_{accel}|}{v_{accel}} min(|v_{accel}|,\ v_{threshold})$$

We then fine-tune how strongly the system reacts to changes in user's motions through a weighted sum $v_{weighted}$ calculated as:

$$v_{weighted} = \alpha \cdot v_{speed} + \beta \cdot v_{\triangle F}$$

which combines the previously calculated v_{speed} with the velocity $v_{\triangle F}$ that corresponds to $\triangle F$. The design tool enables users to dynamically adjust the exoskeleton's impact on their motion by tuning the coefficients α and β. Finally, we feed $v_{weighted}$ into a PID controller that further smoothens the resulting motion and returns the final goal velocity $v_{dynamics}$.

Adding innate patterns. Both microchanges and narrated motions play back sequences of motions. Hence, they can be defined as time-series data comprising a sequence of velocity keyframes $\vec{s} = s_1 ... s_n$. We calculate the target velocities v_{micro} and $v_{narrated}$ as

$$v_{\{micro,narrated\}} = k \cdot s_{\lceil t \cdot \frac{f_s}{1000} \rceil mod\ n}$$

where f_s denotes the custom sampling rate which determines the playback speed, k the factor to scale the motions in size, and t the time in ms passed since the start of the motion. If the user defined a **narrated motion**, $v_{narrated}$ overrides the previously calculated goal velocity $v_{dynamics}$. Finally, if the user designed any additional **microchanges**, v_{micro} is added and the final goal velocity v_{innate} is returned.

Restricting the range of motion. In the last step, the system checks if the user would leave the defined RoM when moving with v_{innate}. In this case, the algorithm sets the calculated velocity to zero, preventing the user from leaving the defined motion range. Inside the RoM, the user can freely move, hence no additional forces are added. If the user starts outside of the indicated motion range, the system only allows the user to move back into this range, blocking movement in the opposite direction.

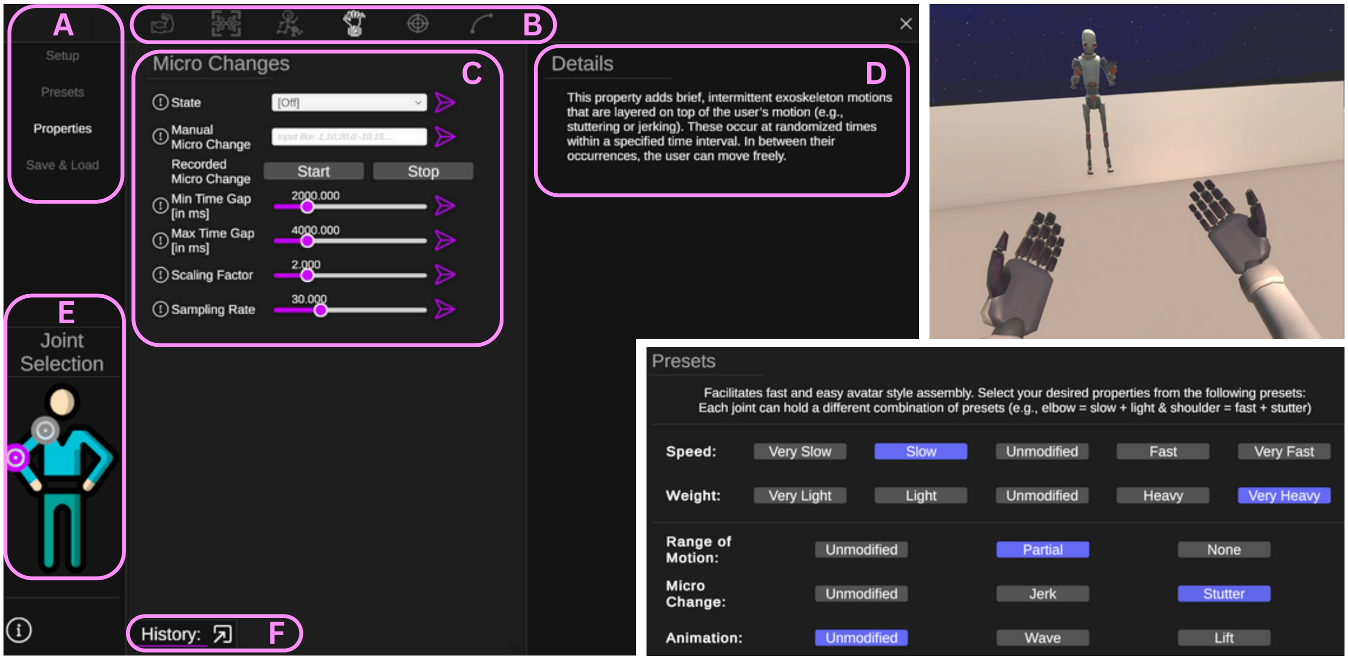

Figure 6: Left: The design tool enables designers to interactively create motion styles. It comprises panels (A) for selecting the step in the process (setup, presets, motion properties, save & load) and (B) for selecting a motion style property. Once a property is selected, (C) designers can adjust its parameters, (D) read its description, (E) select the joint(s) at which they want to experience the property, (F) and retrieve the history of prior configurations. Bottom right: The tool lowers the barrier to entry with five types of presets that designers can try at the click of a button. Top right: The designed motion style can be tested with synchronized visual feedback in a VR environment. Users can see their avatar in a virtual mirror.

Modifying the targeting style. In contrast to the other three dimensions, the targeting style presents a special case as its properties are defined in relation to a known point in space. Due to its dependency on world coordinates and the complex interplay between joints, we calculate the targeting motion style separately from the other properties. As predicting the intended target position of a human motion is an ongoing research area [33, 57], we assume for simplicity that there exists a known point P_{target} to which the user intends to move their hand end effector. Consequently, designers first have to provide the target position $P_{target} = (p_x, p_y, p_z)^T$, with the origin located at the shoulder joint to test how different trajectories and precision affect the motion style.

To modify a user's **trajectory**, the system first calculates a Bézier curve between the user's starting position P_{start} and the denoted target position P_{target} along which the user should move. Given a user's current position P_i, the system then determines the percentage of distance traveled towards P_{target}. From this percentage, we derive the corresponding point on the calculated Bézier curve $P_{bézier}$. Then, we calculate the goal position of the next frame

$$P_{i+1} = P_i + (P_{bézier} - P_i),$$

correcting for the positional offset between $P_{bézier}$ and the user's current position P_i. Finally, an inverse-kinematic (IK) solver calculates the required joint angle configurations. For each joint, we convert the required angular displacements into the goal velocity. Our system implements a linear and quadratic Bézier curve to realize a straight and curved trajectory style.

To enhance **precision**, the system starts guiding the user towards P_{target} with a specified force F if the user is close enough to the target position. If the motions should be imprecise, the algorithm updates the target position P_{target} by adding a random offset within a user-defined interval. We then calculate

$$P_{i+1} = P_i + F \cdot (P_{target} - P_i)$$

and determine the goal velocity with an IK solver as described above.

4.2 Design Tool

We provide a design tool that supports the rapid design and experimentation with the motion style properties. The design tool is implemented with Unity 3D and enables the following process: First, users connect the exoskeleton to the PC and are guided through an initial setup procedure to calibrate the load cell measures. Afterwards, users can freely explore the individual motion properties and parameters, composing them into motion styles (see Figure 6 (left)). Alternatively, they can start by familiarizing themselves with the working principle through pre-implemented presets, which serve to lower the barrier to entry. The tool offers 5 different types of presets, each with different variations (see Figure 6 (right)): 4 variations

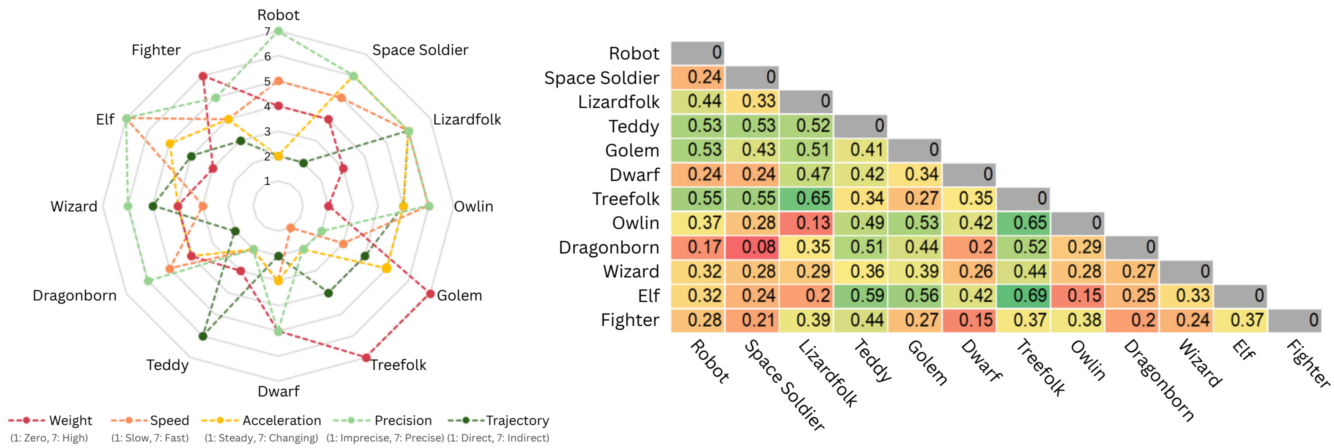

Figure 7: Left: Median ratings for the five quantitative motion properties across all 12 avatars. The results show that the avatar motion styles provide a high coverage of the conceptual space. Right: The normalized root mean square errors (NRMSE) between all pairs of avatars. A NRMSE of 0 indicates identical motion styles, 1 complete opposites. The NRMSEs validate the uniqueness of the avatars' motion styles.

that cover the range from sudden to sustained motions, 4 variations of weight, and 2 pre-implemented RoM constraints, microchanges and narrated motions each. Users can try and combine them at a click of a button. As a safety measure, the user can activate and deactivate the proprioceptive feedback at each joint using a remote control. Once the user created a convincing motion style, they can save the configuration as a .json file. This file can be imported into a VR environment or shared with others.

4.3 VR Environment

The designed motion styles can be tested in combination with a visual avatar representation in a VR environment (see Figure 6 (right)). For demonstration purposes, we provide three example avatars (robot, teddy, and treefolk) and their corresponding proprioceptive motion styles. The environment is implemented for the Oculus Quest with Unity 3D, the meta XR all-in-one SDK and final IK. After an initial calibration, which ensures that the avatar is matched to the user's body proportions, the user can see their avatar in a virtual mirror, switch between avatars and activate or deactivate their corresponding proprioceptive motion feedback. Furthermore, the user can switch to a targeting mode in which random target points are projected within user reach. If the user tries to reach for the point, they feel the impact of the configured targeting styles. As soon as the user reaches the generated point, a new one appears.

5 VALIDATING THE CONCEPTUAL SPACE

An essential quality of a conceptual space is its ability to capture a wide range of options, also referred to as descriptive power [5]. Hence, we validate our conceptual space by demonstrating its capability to describe diverse avatar motion styles. In turn, this enables designers to effectively realize diverse motion styles with the help of *MotionStyler*. Inspired by past works that evaluate the descriptive power of their conceptual spaces by classifying existing systems or case studies (e.g., [12, 55, 63]), we conducted an online user survey to gather the subjective assessment of diverse motion styles for 12 selected avatar species.

Participants. We recruited 19 participants (aged 23 to 62; 10 identified as female, 9 as male) with background in computer science, arts and related fields. An eligibility criterion for the study was knowledge of different avatar species, which we assessed through a questionnaire: Participants self-reported that they often engage in fantasy content (17/19), as well as in role-playing games (12/19), and video games (13/19).

Avatar selection. We created and iteratively refined the set of avatars based on discussions among co-authors. The selected set should (1) cover distinct motion styles, i.e., each avatar is likely to be represented by a unique combination of motion properties, (2) have a high coverage of salient properties, and (3) be informed by popular avatar species occurring in books, movies, video games, or pen-and-paper role-playing games (see subsection 3.1 for an overview). Furthermore, we ensured to include a mix of human and fictional humanoid avatars, to avoid species that are conceptually too similar (e.g., troll and golem), and to exclude species that tend to show aspects of nudity or sexualisation (e.g., merfolk). Based on these considerations, we iteratively reduced the set to 12 avatars, which are listed in Figure 7.

Procedure. The online survey was conducted with SoSciSurvey. First, we provided basic information and collected demographic information. Next, participants characterized the motion styles of the 12 selected avatar species one after the other in a randomized order. For each avatar species, we presented multiple images to elicit particularly salient and generalizable motion properties of a species and reduce bias induced by a specific visual. Based on these images, users filled 7-point semantic differential scale items for the five polar motion properties derived from Laban's space[7]. As the remaining three motion properties have qualitative characteristics, we used open questions with free text fields to gather information about the avatars' innate pattern and physiological constraints (if any). The study took approximately 30 minutes.

Results. Figure 7 (left) shows the median ratings for all 12 avatars for the 5 quantitative motion properties (weight, speed, acceleration, precision, trajectory). It visually demonstrates that each motion property received diverse ratings from low to high across avatars and that the avatars exhibit distinct combinations of motion properties. This enables a unique description of every avatar's characteristic motion style: For instance, the robot, a mechanical device, was characterized with highly precise motions ($\tilde{x} = 7$), straight trajectories ($\tilde{x} = 2$), rather fast speed ($\tilde{x} = 5$), low acceleration ($\tilde{x} = 2$), and no particular impact of weight ($\tilde{x} = 4$). This stands for instance a clear contrast to the treefolk, a heavy creature, which is associated with very high weight ($\tilde{x} = 7$), imprecise motions ($\tilde{x} = 2$), no particularly outstanding trajectory characteristics ($\tilde{x} = 4$), but very slow motions ($\tilde{x} = 1$), and low acceleration ($\tilde{x} = 2$). From Figure 7 (left), it is apparent that the selected set of avatars provides a high coverage of the conceptual space.

In addition, we systematically validate the distinctiveness of the motion styles by calculating the normalized root mean square error (NRMSE) between all pairs of avatars based on the collected median ratings as

$$\text{NRMSE} = \frac{\text{RMSE}}{y_{max} - y_{min}}$$

where y_{min} and y_{max} are the minimum and maximum values of the semantical differential scale items (i.e., 1 and 7, respectively) and the RMSE is calculated as

$$\text{RMSE} = \sqrt{\frac{\sum_{p \in Prop}(avatar_{i,p} - avatar_{j,p})^2}{|Prop|}}$$

Here, $avatar_{i,p}$ and $avatar_{j,p}$ describe the median ratings of any two avatars $avatar_i$ and $avatar_j$ for a property $p \in Prop$ with $Prop = \{\text{weight, speed, accuracy, precision, trajectory}\}$. The resulting matrix is shown in Figure 7 (right). A NRMSE of 0 means no difference in motion style between the pair of avatars, 1 indicates the maximum possible difference with respect to every motion property. Of note, not every avatar necessarily exhibits extreme values (i.e., only ratings of 1 or 7) for all properties, and the NRMSE between an avatar exhibiting only maximum ratings and an avatar without any salient traits (i.e., only ratings of 4) is 0.5. Thus, we consider the motion styles of avatars with an NRMSE of 0.5 or higher as highly distinct. Our results reveal that the NRMSEs vary between the different avatars, with the highest difference between treefolk and elf (0.69) and the lowest between space soldier and dragonborn (0.08). Furthermore, the avatars with the most unique motion styles, i.e., those with the highest amount of NRMSEs of 0.5 or higher, are the treefolk with 6 highly distinct NRMSEs, the teddy (5), and the golem (4). The dwarf, fighter and wizard have the least unique motion styles. However, each of their motion styles exhibits individual motion properties with specifically salient ratings (cf., Figure 7 (left)). The uniqueness of each avatar's motion style is further pinpointed by the qualitative feedback, capturing salient innate patterns and physiology. For instance, while the space soldier and dragonborn had the lowest NRMSE, 15/19 participants indicated that the space soldier exhibits considerable restrictions in the range of motion due to the armor, while the dragonborn did not elicit such strong associations. Similarly, 16/19 participants identified a RoM constraint for the treefolk as the branches would make the avatar *"very inflexible"* (P16), resulting in *"stiff motions"* (P11). This considerably differs from other avatars which were less frequently associated with RoM constraints, but rather with specific innate patterns. For instance, the lizardfolk would perform *"sudden small movements"* (P10), while the old wizard, which had low NRMSEs, would be *"trembling"* (P6) when moving.

Considering the NRMSEs in combination with the variety of qualitative feedback that captures any innate patterns and physiological salience, the results of the survey confirm that our conceptual space can effectively describe diverse, unique motion styles. In the next section, we demonstrate that *MotionStyler* enables designers to create and render such motion styles.

6 USER STUDY

To empirically validate *MotionStyler*'s capabilities and the potential of proprioceptive motion styles, we conducted a user study. The objective of the study is to (1) investigate how well *MotionStyler* helps designers to create diverse motion styles, and (2) evaluate the impact of proprioceptive motion styles on the VR experience.

We recruited 12 participants (aged 21 to 33; 10 identified as male, 2 as female). All participants had normal or corrected-to-normal vision and had prior experience with VR; six participants indicated to be frequent VR users. Two participants are experienced hapticians, and 3 have tried out or developed exoskeletons themselves.

Due to the two-fold purpose of the study, we split the experiment into two tasks with two separate goals. The same 12 participants took part in both parts. We report on the two tasks, including their method and results separately below:

6.1 Task 1: *Creating Proprioceptive Motion Styles*

The aim of the first task was to assess if users are able to understand and use the motion style properties and if they can design their own proprioceptive motion styles. For this, we used *MotionStyler*'s design tool and the arm-based exoskeleton.

Procedure. First, the experimenter explained the design tool's functionalities and then helped the user to attach and calibrate the exoskeleton. Next, the participant was tasked to familiarize with the tool's offered presets. Once confident, participants could freely use the tool to create a motion style for an avatar of their choice. They were asked to think out loud, while the experimenter took notes and helped out if problems occurred. We concluded the session with a SUS questionnaire and custom Likert-scale items assessing how well the tool supported user's creativity and the usefulness of the offered presets, and a semi-structured interview to investigate encountered challenges, the appropriateness of the selected motion properties, and future use cases for proprioceptive

[7]The five polar properties consist of weight (1: zero, 7: high weight), speed (1: slow, 7: fast), acceleration (1: steady, 7: changing), precision (1: imprecise, 7: precise) and trajectory (1: direct, 7: indirect)

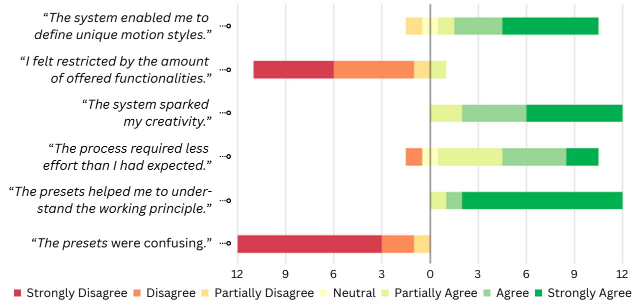

Figure 8: Results of the 7-point Likert scale show that *MotionStyler* supports users in creatively exploring a diverse range of motion styles.

motion styles. The Likert-scale items are shown in Figure 8. Task 1 took 60 minutes and was audio-recorded.

6.1.1 Results.

Designed motion styles. The results of the Likert items show that the design tool could effectively support participants in designing unique motion styles and that it sparked their creativity (see Figure 8). This was also reflected in the diversity of motion styles explored by the participants: For instance, P12 decided to design a motion style for a robot with a damaged shoulder: First, P12 created the motion style of a brand-new robot with an unconstrained RoM, and fast and precise motions. Next, P12 modeled the malfunctions by locally constraining the RoM in the shoulder joint, adding weight and microchanges to simulate stuttering. This demonstrates the system's flexibility to design motion styles at a joint-level. Furthermore, P6 designed the motion style of a strong knight by combining fast movements with high weight. Because the knight should lift a heavy sword, P6 added microchanges to mimic muscle twitches. While many participants created diverse motion styles for fantasy characters, including a dwarf (P7), golem (P1, P4), a troll with slow, heavy movements (P10), or a lightweight elf (P1), other participants designed motion styles for non-fictional characters. For instance, P2 and P8 simulated an elderly's way of moving, combining jerking motions with increased weight; others used the weight property to experiment with the impact of different environmental conditions on human body motions, such as when moving underwater (P3) or floating in space (P11).

Usability, challenges, and future improvements. The design tool achieved a SUS score of 72.5, indicating good usability [3]. Overall, the participants were positive about the offered functionalities and several participants emphasized they found the motion properties generally easy to learn and understand (P1, P9, P11, P12). However, because of the large number of possible parameters, all participants agreed that they would require additional time to learn the details of the parameters. In this regard, many participants explicitly appreciated the presets as a valuable entry point (P2, P6, P8-P11). This was also reflected in their Likert ratings (see Figure 8). To further enhance the usability, participants suggested to expand the offered presets or to provide a library of pre-defined avatar motion styles from which they can select (P4, P7, P10, P11). Notably,

Figure 9: To investigate how different proprioceptive motion styles affect avatar embodiment in VR, participants embodied a robot, teddy and treefolk avatar in our user study.

this feature is already supported through the *save & load* option in the design tool. Finally, participants wished for visualizations and simulations that illustrate how the motion properties would affect the body (P1, P2, P5, P6, P8, P10, P12), an important consideration for future iterations of the tool.

Utility of proprioceptive motion styles. Participants identified various use cases for proprioceptive motion styles, emphasizing the broad applicability of the proposed concept: While the most frequently mentioned use case is gaming in VR (P1–P5, P7–P12), participants also saw potential for teleoperation, where users would embody a remote robot while directly feeling its mechanical constraints (P3, P12). Beyond VR, P1 and P10 also highlighted how these proprioceptive motion styles could generally enhance empathy towards others by simulating, e.g., a body *"that is really heavy or that is old or where you have certain limitations in movement"* (P10). Furthermore, they can help users to replicate the motion style of their trainer for motion learning (P8, P12), support the rehabilitation process (P9, P11) or improve overall performance by enhancing targeting precision for physical activities (P5, P7).

6.2 Task 2: *Experiencing Motion Styles in VR*

The second task aimed to evaluate how proprioceptive motion styles influence agency, bodily self-identification with the avatar, and user behavior in VR.

6.2.1 Method. To understand the effects on avatar embodiment in VR, we conducted a controlled experiment in which we compare the effects of proprioceptive feedback with the condition in which no haptic feedback is provided. For this, we used the arm-based exoskeleton and the VR environment described in subsection 4.3. In the following, we first describe the avatars chosen for the experiment, and then the study design.

Selected avatars. Based on the results of the survey presented in Section 5, we selected the robot, teddy, and treefolk avatars as they (1) have several salient motion properties[8], (2) exhibit particularly distinct combinations of motion properties with high NRMSEs, and (3) have received interesting qualitative feedback. For the

[8] at least 3 properties with median <= 2 or >=6

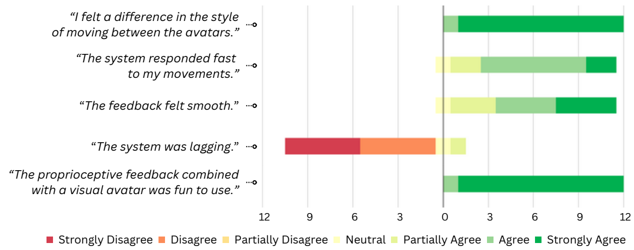

Figure 10: Results of the 7-point Likert scale show that the designed motion styles were distinct, smooth, and enjoyable.

avatars, we selected Unity assets that meet the usual high quality standards of rendering in VR. The selected visual representations of the avatars can be seen in Figure 9. We intentionally removed shadows from the VR scene to keep the visual focus solely on the avatar. Informed by the survey results, we used *MotionStyler* to implement the avatars' proprioceptive motion styles. For the robot, we chose high speed and rapid, constant acceleration. As the robot received a neutral weight rating, we refrained from altering the impact of weight. To realize the teddy's motion style, we combined slow speed with slow acceleration and low gravitational impact. The latter makes the user's motions more lightweight. Contrary, the treefolk avatar was realized with very high gravitational impact, very slow speed, slow acceleration and a reduced RoM. We fine-tuned the parameters through a series of pilot tests with the co-authors and two additional testers who were not involved in the main study.

Experimental design and independent variables. Our study followed a within-subjects study design in which each participant embodied each avatar exactly once in the standard setup with only visual feedback, which serves as our baseline, and once with additional proprioceptive motion feedback. Hence, we consider two independent variables (IVs):

- AUGMENTATION has two levels: VISUAL and VISUO-PROPRIOCEPTIVE.
- AVATAR has three levels: ROBOT, TEDDY and TREEFOLK.

We counterbalanced the conditions for AVATAR with a balanced Latin square. For each avatar, participants experienced both AUGMENTATION levels sequentially, but in a randomized order.

Experimental protocol. We first guided participants through the calibration routine to adjust the avatar's size to the participant to ensure high visuo-proprioceptive alignment and then started with the controlled study. For each condition, participants were asked to perform a series of body motions announced by the experimenter, followed by free movement to give them sufficient time to familiarize themselves with each avatar. This is crucial to develop a sense of embodiment towards a virtual avatar [19, 34]. Additionally, participants could see their avatar in a virtual mirror to enhance their behavioral responses [21].

We assessed the effects of the motion style on the experience in VR through several measures. These have been informed by standardized questionnaire items and insights from pilot studies: First, after each condition, we assessed perceived agency using an adapted version of the Embodiment Questionnaire by Gonzalez-Franco et al., aggregating the results of items Q6, Q7 and Q9 to calculate the agency score [23]. We further added a Likert item to assess if users had adopted the avatar's way of moving as an indicator of any potential behavioral changes that might occur in response to proprioceptive feedback. Second, after being presented with a proprioceptive motion style, we asked participants to rate on a 7-point Likert scale if the presented motion style matched their expectations and, after experiencing both levels of AUGMENTATION for an avatar, if the proprioceptive motion style enhanced self-identification with their avatar. The Likert-scale items of the questionnaire are shown in Figures 11 and 12. We use these measures for statistical analyses.

Finally, we concluded the experiment with another custom questionnaire assessing the responsiveness and quality of the rendered feedback (see Figure 10), and a semi-structured interview to more in-depth insights into user's expectations and preferences. As the custom questionnaire consists of single-item global assessments of the system, no statistical tests are performed for it. Task 2 took about 30 minutes and was audio-recorded.

Data analysis. We apply non-parametric tests to analyze the ordinal Likert items: First, we apply the Aligned Rank Transformation (ART) RM ANOVAS as proposed by Wobbrock et al. [70] to investigate interaction and main effects between AVATAR and AUGMENTATION on agency and motion adoption. For significant results, we follow up with the ART-C procedure as suggested by Elkin et al. [17]. We report on partial eta-square η_p^2 as the measure of effect size and classify it as small (> .01), medium (> .06), or large (> .14) [10]. Second, to analyze the effects of AVATAR on expectation matches and bodily self-identification when proprioceptive feedback was provided, we apply the Friedman test. For significant results, we follow up with pairwise Wilcoxon signed-rank tests. We report Kendall's W as the measure of the effect size. For Kendall's W, we use the suggestions by Cohen [10] to classify them as small (> .10), medium (> .30), or large (> .50). Third, to analyze correlations between Likert items where appropriate, we calculate the Spearman correlation coefficient ρ due to its fit for ordinal data. The coefficient ranges from -1 to 1, where $\rho > 0$ indicates a positive correlation and $\rho < 0$ a negative one. We classify $|\rho|$ as weak (> .20), moderate (> .50), and strong (> .80) [10].

6.2.2 Results.

User experience, preferences, and expectations. Participants agreed that the proprioceptive motion styles of the three avatars felt distinct, were enjoyable, and that the haptic rendering system created smooth and responsive proprioceptive feedback (see Figure 10), confirming that *MotionStyler* can effectively render different motion styles. Participants further confirmed that the implemented motion styles largely matched with how they expected the avatar's motion to feel ($\tilde{x} = 6$), however, with individual differences across avatars (ROBOT: $\tilde{x} = 7$, TEDDY: $\tilde{x} = 3.5$, TREEFOLK: $\tilde{x} = 6$). A Friedman test revealed significant effects of AVATAR on expectation match ($\chi^2(2) = 9.38, p < .001$) with a medium effect size ($W = .391$). Post-hoc Wilcoxon signed-rank tests revealed a significantly higher expectation match for ROBOT compared to TEDDY ($p < .05$). The results are shown in Figure 11 (left). The differences in expectations also affected user preferences: The treefolk avatar was the most preferred for the majority of participants as they felt that it closely

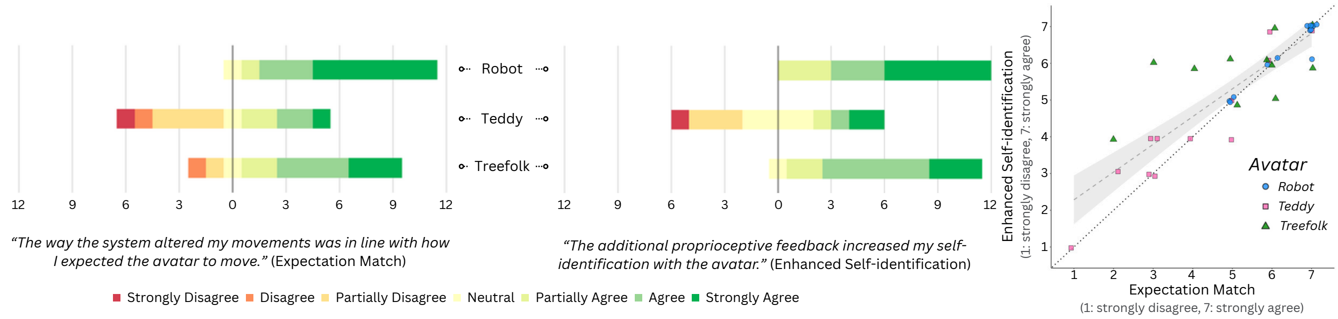

Figure 11: Left: Results of the 7-point Likert scale show that the proprioceptive motion styles of the robot aligned most with participants' expectations, followed by the treefolk and the teddy avatar. The latter elicited most mixed reactions. Middle: Similarly, our results show that the proprioceptive motion styles enhanced participants' self-identification with the avatar, with the strongest effect for the robot, followed by the treefolk and the teddy avatar. Right: A Spearman correlation between the two Likert items reveals a strong positive correlation between the expectation match and enhanced self-identification.

matched their expectations: *"it was the best because there I could really feel the stiffness of the movement"* (P10). Contrarily, the teddy often was least preferred and received mixed opinions: *"So I like the [low weight] and I could directly associate it with the teddy. However, the slow moving joints were kind of surprising to me. I didn't expect them."* (P12). While some, like P2, felt that an expectation mismatch would not diminish the overall experience, others (P4, P12) reported that it might have a negative impact. Interestingly, some participants also reported that their expectations adopted positively over time: *"for the tree one, in the beginning [...] it didn't match with the motion style, but after just moving around a bit and looking in the mirror, it kind of matched"* (P3). These discussions surface the importance of user expectations when designing proprioceptive motion styles, as participants may have individual associations with particular avatars that can either positively or negatively affect the overall VR experience.

Effects on bodily self-identification with the avatar. Bodily self-identification is an important factor to enhance avatar embodiment in VR [23]. After experiencing the proprioceptive motion styles, we asked participants to rate if it enhanced self-identification with the avatar. The results are shown in Figure 11 (middle). Overall, participants agreed that the proprioceptive motion styles improved self-identification with their avatar ($\tilde{x} = 6$), although ratings varied between the Robot ($\tilde{x} = 6.5$), Teddy ($\tilde{x} = 4$) and Treefolk ($\tilde{x} = 6$). A Friedman test revealed significant effects of avatar on self-identification ($\chi^2(2) = 9.05$, $p < .05$) with a medium effect size ($W = .377$). However, post-hoc Wilcoxon signed-rank tests did not show any significant differences. Participants explained that the effect was strongly tied to whether the motion style aligned with their personal expectations (P1, P3, P5, P9-P12): *"When it works together with the expectations, it really puts your embodiment to another level"* (P5). Similarly, P10 noted that proprioceptive feedback *"made me empathize with the character more in the sense that [...] I understood more how this character would move and what it would feel like to be this character."* As the impact of users' expectations was a recurring theme in the interviews, we followed up with a Spearman correlation between the two Likert items capturing expectation matches and self-identification (see Figure 11 (right)). The results indeed revealed a strong positive correlation ($\rho = 0.87$, $p < .001$), indicating the more the proprioceptive feedback matched the personal expectation, the more the participants could self-identify with their avatar.

Effects on agency. Agency is another important aspect of embodiment [23]. As external forces that modify a user's inherent motion might affect the sense of agency, we examined how the proprioceptive motion styles impacted the agency ratings. Since the visual condition acts as our baseline, we first confirmed with a Friedman test that avatar did not have a significant effect on agency ($\chi^2(2) = 2.07$, $p > .05$) when only visual feedback was provided. Next, the ART revealed a significant main effect of avatar on agency ($F(2, 55) = 7.59, p < .01$) with a large effect size ($\eta_p^2 = 0.22$). ART-C pairwise post-hoc tests revealed a significant loss in agency for Teddy compared to Robot ($p < .01$) and Treefolk ($p < .01$). We further found a significant main effect of augmentation on agency, with visuo-proprioceptive having a significantly lower agency score compared to visual ($F(1, 55) = 40.887, p < .001$) with a large effect size ($\eta_p^2 = 0.43$). Finally, we also found a significant interaction effect ($F(2, 55) = 5.379, p < .01$) with a large effect size ($\eta_p^2 = 0.16$). ART-C pairwise post-hoc tests revealed a significant loss in agency for visuo-proprioceptive compared to visual for Treefolk ($p < .05$) and Teddy ($p < .001$). Furthermore, we found a significant loss in agency for Teddy in the visuo-proprioceptive condition compared to Robot ($p < .001$) and Treefolk ($p < .001$) in the visual condition. Additionally, within the visuo-proprioceptive condition, we further found a significantly lower agency for Teddy compared to Robot ($p < .001$) and Treefolk ($p < .05$). Although the overall agency score decreased from $\tilde{x} = 7$ to $\tilde{x} = 6$ when proprioceptive feedback was provided, it is apparent that participants still felt in control of their motion. The highest scores were achieved for Robot and Treefolk. This is striking as especially the treefolk avatar considerably restricted the user's motion freedom. In the follow-up interviews, participants elaborated that if *"the style matches the character, you don't feel restrained even if the exoskeleton is restraining your movements because you feel like there is a connection between the two"* (P4) and

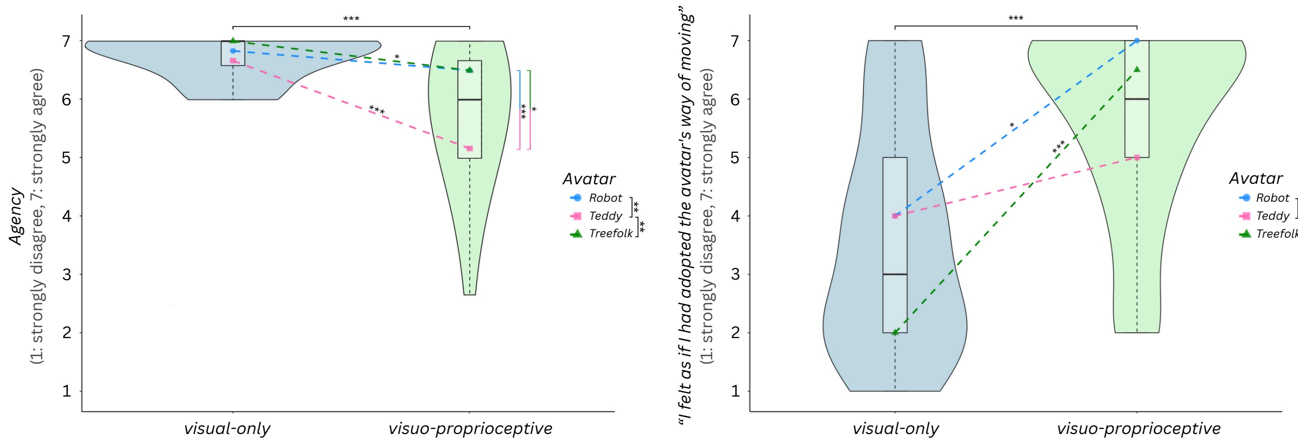

Figure 12: Left: The agency score represents an aggregated measure of users' responses to the items Q6, Q7 and Q9 in the Embodiment Questionnaire [23]. Our results show that agency was significantly reduced if proprioceptive feedback was provided, with a particularly strong effect for the teddy avatar. However, participants still rated the sense of agency rather positively. The robot and treefolk avatars achieved the highest scores. Right: Users indicated that they rather adopted their own motion style to that of the avatar if proprioceptive feedback was provided, with particularly strong effects for the robot and treefolk avatars.

that the loss of agency can even be a desirable property *"by design"* (P5). As for the bodily self-identification, we followed up with another Spearman correlation to investigate a potential relation between user expectations and agency. However, we did not find a significant correlation ($\rho = 0.23$, $p > .05$) between the two items.

Effects on adoption to avatar's motion style. Prior work has shown that a sense of embodiment can elicit changes in users' behavior [72]. Our participants self-reported a greater tendency to adapt their movement to the avatar's motion style when proprioceptive feedback was provided ($\tilde{x} = 6$) than without it ($\tilde{x} = 3$). The ART test revealed a significant main effect of AVATAR on motion adoption ($F(2, 55) = 3.197, p < .05$) with a medium effect size ($\eta_p^2 = 0.1$). Post-hoc tests revealed a significantly higher effect on motion adoption for ROBOT compared to TEDDY ($p < .05$). We also found a significant main effect of AUGMENTATION on motion adoption, with VISUO-PROPRIOCEPTIVE having significantly higher ratings compared to VISUAL ($F(1, 55) = 27.443, p < .001$) with a large effect size ($\eta_p^2 = 0.33$). We did not find a significant interaction effect ($F(2, 55) = 2.794, p > .05, \eta_p^2 = 0.07$). However, as the proprioceptive feedback implemented for the different avatars affects the user's motion to varying degrees, and as we were specifically interested in whether this has a positive or negative effect on the motion adoption ratings for the individual avatars, we followed up with ART-C, as these contrast tests do not need to follow significant omnibus test results if in line with the core of the research question [17]. The tests revealed a significant increase of motion adoption for VISUO-PROPRIOCEPTIVE compared to VISUAL for the ROBOT ($p < .05$) and TREEFOLK ($p = .001$), but not for the TEDDY. The results are shown in Figure 12. As P12 elaborated, *"I learned I have to move very slowly because of the feedback, and so I have to think differently. Now I have to think like a tree, for example. I have to plan my movements more because I cannot easily redo them."* A follow-up Spearman correlation revealed a moderate positive correlation ($\rho = 0.62$, $p < .001$) between user expectations and motion adoption and a strong positive correlation ($\rho = 0.80$, $p < .001$) between self-identification and motion adoption, indicating that the more an avatar's proprioceptive motion style aligned with user expectations – and consequently the more they could self-identify with the avatar – the more users adapted their way of moving to the proposed motion style.

7 DISCUSSION, LIMITATIONS AND FUTURE WORK

In the following, we discuss our findings and identify directions for future work:

Creating expressive and diverse proprioceptive motion styles. One objective of this work was to enable designers to create distinct and expressive motion styles. The motion styles designed by us and our study participants for Task 1 demonstrated that the proposed motion properties serve as an extensive foundation for creating a wide range of motion styles. For instance, participants were able to select desired properties such as microchanges and weight, identify suitable parameters, and effectively combine them into meaningful motion styles that were associated with both fictional and non-fictional characters. Although the extensive range of properties and parameters allows experienced users to create complex motion styles, it also presents a substantial learning curve for novices. Presets, which abstract from the details of individual motion properties, helped lower this barrier to entry. Furthermore, participants felt inspired by the range of possibilities and argued that such proprioceptive motion styles offer intriguing possibilities even beyond VR. While we implemented the motion properties for the arms, the motion dynamics, innate patterns, and physiology concepts also generalize to other body parts, such as the hands and legs. The targeting style, however, is less directly transferable due to its link to grasping tasks. Future work can reinterpret it in domain-specific contexts, such as for locomotion. Here, a proprioceptive device may alter the user's walking trajectory to be more or less direct or precise. Previous work has demonstrated the feasibility of this approach [60], which provides an interesting starting point for aligning the user's physical gait with an avatar's expected gait. Finally, another important avenue to broaden the applicability of the proposed concept is to extend the space to non-humanoid avatars, which typically exhibit different or additional limb structures [64]. We expect that this will primarily affect the physiological dimension of our space, but will also pose new conceptual challenges for the design of appropriate proprioceptive motion feedback.

Enhancing avatar embodiment in VR with proprioceptive motion styles. The second objective of this work was to investigate how proprioceptive motion styles enhance embodiment in VR. Task 2 of our user study showed that these motion styles not only enhance immersion and enjoyment but indeed also positively impact key aspects of avatar embodiment. First, we found that proprioceptive motion styles enhanced bodily self-identification with the avatar compared to conditions with only visual feedback. Second, although agency was slightly reduced when proprioceptive feedback was provided, participants found this acceptable or even desirable when it aligned with the avatar's motion capabilities. This suggests that agency can be purposefully modulated to support avatar embodiment. Third, participants reported that they adapted their motion planning and execution in response to the proprioceptive motion styles when it matched with the avatar, indicating potential behavioral changes akin to the Proteus effect [72]. In line with this, prior work theorized that the Proteus effect could be related to the self-identification process [15]. The strong correlation between self-identification and motion style adoption would support this hypothesis. These phenomena warrant further investigation in future studies. Furthermore, our results highlight the potential of proprioceptive motion styles that combine multiple properties. While a few prior studies have explored the impact of individual properties like weight perception [35], the effects of other properties, such as RoM constraints or targeting styles, and any potential interaction effects between properties remain under-explored. Finally, future work should also investigate the impact of proprioceptive motion styles on embodiment in various contexts, such as gaming, for more diverse user demographics and user studies with larger sample sizes, across a broader range of avatars, and in combination with other feedback modalities like auditory cues. Initial indications suggest that these combinations might further enhance avatar embodiment [43].

Customizing proprioceptive motion styles to match user expectations. Participant responses revealed the critical role of personal expectations and associations with avatars in shaping the VR experience. While the motion styles of the robot and treefolk avatars were largely in line with the expectations of our study participants, the teddy received mixed reactions and consistently lower scores due to diverging associations. Our results indicate that such mismatches might negatively affect important qualities of the VR experience, including bodily self-identification with the avatar. This echoes findings from prior work, where mismatches in the auditory stimulus diminished the experience [43]. While there may be common associations for some avatars, as also indicated in Section 5, our findings highlight the importance of aligning motion styles with user expectations. Future work should explore how to facilitate customization of motion styles for designers or even end-users. With the recent rise of LLMs, generating or modifying proprioceptive motion styles from natural language descriptions presents a particularly interesting avenue for future work.

MotionStyler implementation. We prototypically implemented the motion styles in an arm-based exoskeleton with two active DoFs, allowing for a technically focused yet conceptually broad exploration. In the future, the prototype can be extended to more DoFs or even to both arms to create more diverse sensations. As the system needs one load cell for each active joint, it can be expanded to more DoFs by adding more motors and load cells accordingly. Based on our approach for realizing and combining motion properties, we also expect our method to be transferable to other parts of the body, such as hands or legs. Furthermore, we chose an exoskeleton as it enables us to render a diverse range of proprioceptive feedback within one device. Future work should consider how these properties can be achieved with other proprioceptive feedback devices, such as EMS, with a lighter and more portable form factor, and how the quality of the rendered sensations compares to devices that target one specific motion property such as PumpVR [35]. Finally, our study showed that the design tool should be further improved through visualizations and simulations. It remains an interesting question for future work how best to simulate and visualize the effects of an exoskeleton on the user's body in a way that is easily understood by novice users.

8 CONCLUSION

This work proposes to leverage proprioceptive feedback to align users' physical movements with the expected motion style of their avatar to enhance avatar embodiment in VR. In order to design these proprioceptive motion styles, we introduce a conceptual space of distinct motion properties for humanoid avatars, clustered into four key dimensions: *motion dynamics* describe the the avatar's body weight along its characteristic motion speed and acceleration; *innate patterns* comprise avatar-specific motions that are either layered on top of the user's inherent motions, such as stuttering, or played back on demand; *physiology* describes any potential restrictions in the joints' range of motion, and *targeting style* the precision and trajectory with which the avatar typically approaches a target. These properties can be combined into expressive proprioceptive motion styles. We operationalize this concept with *MotionStyler*, a proof-of-concept system that renders these proprioceptive motion styles in real-time in VR using an arm-based exoskeleton. An additional design tool aids designers to create custom motion styles. We validate the descriptive power of the conceptual space through an online survey. The results of a user study further confirm that *MotionStyler* enables designers to create distinct motion styles and that such proprioceptive motion styles positively impact avatar embodiment in VR if they match the way the user expects the avatar to move. We hope that this work inspires future work to investigate the potential of proprioceptive motion feedback to enhance avatar embodiment.

ACKNOWLEDGEMENTS

We thank all participants of our user studies. We also thank the reviewers for their valuable comments.

REFERENCES

[1] Alexandra Bacula and Amy LaViers. 2018. Character Recognition on a Humanoid Robotic Platform via a Laban Movement Analysis. In *Proceedings of the 5th International Conference on Movement and Computing* (Genoa, Italy) *(MOCO '18)*. Association for Computing Machinery, New York, NY, USA, Article 17, 8 pages. https://doi.org/10.1145/3212721.3212836

[2] Alexandra Bacula and Amy LaViers. 2021. Character Synthesis of Ballet Archetypes on Robots Using Laban Movement Analysis: Comparison Between a Humanoid and an Aerial Robot Platform with Lay and Expert Observation. *International Journal of Social Robotics* 13, 5 (Aug. 2021), 1047–1062. https://doi.org/10.1007/s12369-020-00695-0

[3] Aaron Bangor, Philip Kortum, and James Miller. 2009. Determining what Individual SUS Scores Mean: Adding an Adjective Rating Scale. *Journal of Usability Studies* 4, 3 (2009), 114–123.

[4] Irmgard Bartenieff and Martha Davis. 1965. *Effort-shape Analysis of Movement: The Unity of Expression and Function.* Albert Einstein College of Medicine, Yeshiva University.

[5] Michel Beaudouin-Lafon. 2004. Designing Interaction, Not Interfaces. In *Proceedings of the Working Conference on Advanced Visual Interfaces* (Gallipoli, Italy) *(AVI '04)*. Association for Computing Machinery, New York, NY, USA, 15–22. https://doi.org/10.1145/989863.989865

[6] Leslie Bishko. 2014. *Animation Principles and Laban Movement Analysis: Movement Frameworks for Creating Empathic Character Performances.* ETC Press, Pittsburgh, PA, USA, 177–203.

[7] Matthew Botvinick and Jonathan Cohen. 1998. Rubber Hands 'Feel' Touch That Eyes See. *Nature* 391, 6669 (Feb. 1998), 756–756. https://doi.org/10.1038/35784

[8] Sidney Bovet, Henrique Galvan Debarba, Bruno Herbelin, Eray Molla, and Ronan Boulic. 2018. The Critical Role of Self-Contact for Embodiment in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 24, 4 (2018), 1428–1436. https://doi.org/10.1109/TVCG.2018.2794658

[9] Yingjie Chang, Junyu Chen, Yilong Lin, Xuesong Zhang, and Seungwoo Je. 2025. HapticWings: Enhancing the Experience of Extra Wing Motions in Virtual Reality through Dynamic 2D Weight Shifting. In *Proceedings of the 2025 ACM Designing Interactive Systems Conference (DIS '25)*. Association for Computing Machinery, New York, NY, USA, 15–27. https://doi.org/10.1145/3715336.3735755

[10] Jacob Cohen. 1988. *Statistical Power Analysis for the Behavioral Sciences.* Routledge. https://doi.org/10.4324/9780203771587

[11] Fabien Danieau, Julien Fleureau, Philippe Guillotel, Nicolas Mollet, Anatole Lécuyer, and Marc Christie. 2012. HapSeat: Producing Motion Sensation with Multiple Force-feedback Devices Embedded in a Seat. In *Proceedings of the 18th ACM Symposium on Virtual Reality Software and Technology* (Toronto, Ontario, Canada) *(VRST '12)*. Association for Computing Machinery, New York, NY, USA, 69–76. https://doi.org/10.1145/2407336.2407350

[12] Kurtis Danyluk, Barrett Ens, Bernhard Jenny, and Wesley Willett. 2021. A Design Space Exploration of Worlds in Miniature. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 122, 15 pages. https://doi.org/10.1145/3411764.3445098

[13] Nina Döllinger, David Mal, Sebastian Keppler, Erik Wolf, Mario Botsch, Johann Habakuk Israel, Marc Erich Latoschik, and Carolin Wienrich. 2024. Virtual Body Swapping: A VR-Based Approach to Embodied Third-Person Self-Processing in Mind-Body Therapy. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 110, 18 pages. https://doi.org/10.1145/3613904.3642328

[14] Florian Dufresne, Tommy Nilsson, Geoffrey Gorisse, Enrico Guerra, André Zenner, Olivier Christmann, Leonie Bensch, Nikolai Anton Callus, and Aidan Cowley. 2024. Touching the Moon: Leveraging Passive Haptics, Embodiment and Presence for Operational Assessments in Virtual Reality. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 413, 18 pages. https://doi.org/10.1145/3613904.3642292

[15] Louise Dupraz, Marine Beaudoin, Michel Guerraz, and Julien Barra. 2024. Does the Avatar Embodiment Moderate the Proteus Effect? *International Journal of Human-Computer Studies* 187 (2024), 103272. https://doi.org/10.1016/j.ijhcs.2024.103272

[16] A. Egges, T. Molet, and N. Magnenat-Thalmann. 2004. Personalised Real-time Idle Motion Synthesis. In *12th Pacific Conference on Computer Graphics and Applications, 2004. PG 2004. Proceedings.* 121–130.

[17] Lisa A. Elkin, Matthew Kay, James J. Higgins, and Jacob O. Wobbrock. 2021. An Aligned Rank Transform Procedure for Multifactor Contrast Tests. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 754–768. https://doi.org/10.1145/3472749.3474784

[18] Sarah Fdili Alaoui, Jules Françoise, Thecla Schiphorst, Karen Studd, and Frederic Bevilacqua. 2017. Seeing, Sensing and Recognizing Laban Movement Qualities. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4009–4020. https://doi.org/10.1145/3025453.3025530

[19] Martin Feick, André Zenner, Simon Seibert, Anthony Tang, and Antonio Krüger. 2024. The Impact of Avatar Completeness on Embodiment and the Detectability of Hand Redirection in Virtual Reality. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 548, 9 pages. https://doi.org/10.1145/3613904.3641933

[20] Elisa Raffaella Ferrè, T Frett, P Haggard, and Matthew R Longo. 2019. A Gravitational Contribution to Perceived Body Weight. *Scientific Reports* 9, 1 (2019), 11448.

[21] BoYu Gao, Joonwoo Lee, Huawei Tu, Wonjun Seong, and HyungSeok Kim. 2020. The Effects of Avatar Visibility on Behavioral Response with or without Mirror-Visual Feedback in Virtual Environments. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. 780–781. https://doi.org/10.1109/VRW50115.2020.00241

[22] Adélaïde Genay, Anatole Lécuyer, and Martin Hachet. 2021. Being an Avatar "for Real": A Survey on Virtual Embodiment in Augmented Reality IEEE Journals & Magazine IEEE Xplore. *IEEE Transactions on Visualization and Computer Graphics* 28, 12 (2021), 5071–5090. https://doi.org/10.1109/TVCG.2021.3099290

[23] Mar Gonzalez-Franco and Tabitha C Peck. 2018. Avatar Embodiment. Towards a Standardized Questionnaire. *Frontiers in Robotics and AI* 5 (June 2018), 74. https://doi.org/10.3389/frobt.2018.00074

[24] Antti Granqvist, Tapio Takala, Jari Takatalo, and Perttu Hämäläinen. 2018. Exaggeration of Avatar Flexibility in Virtual Reality *(CHI PLAY '18)*. Association for Computing Machinery, New York, NY, USA, 201–209. https://doi.org/10.1145/3242671.3242694

[25] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 1991–1995. https://doi.org/10.1145/2858036.2858487

[26] Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. 2019. PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 227–240. https://doi.org/10.1145/3322276.3322302

[27] Takeru Hashimoto, Shigeo Yoshida, and Takuji Narumi. 2023. SomatoShift: A Wearable Haptic Display for Somatomotor Reconfiguration via Modifying Acceleration of Body Movement. In *ACM SIGGRAPH 2023 Emerging Technologies* (Los Angeles, CA, USA) *(SIGGRAPH '23)*. Association for Computing Machinery, New York, NY, USA, Article 17, 2 pages. https://doi.org/10.1145/3588037.3595390

[28] Mahmoud Hassan, Florian Daiber, Frederik Wiehr, Felix Kosmalla, and Antonio Krüger. 2017. FootStriker: An EMS-based Foot Strike Assistant for Running. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 1, Article 2 (mar 2017), 18 pages. https://doi.org/10.1145/3053332

[29] Seongkook Heo, Christina Chung, Geehyuk Lee, and Daniel Wigdor. 2018. Thor's Hammer: An Ungrounded Force Feedback Device Utilizing Propeller-Induced Propulsive Force. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3173574.3174099

[30] Ryota Ito, Nami Ogawa, Takuji Narumi, and Michitaka Hirose. 2019. Do We Have to Look at the Mirror All the Time? Effect of Partial Visuomotor Feedback on Body Ownership of a Virtual Human Tail. In *ACM Symposium on Applied Perception 2019* (Barcelona, Spain) *(SAP '19)*. Association for Computing Machinery, New York, NY, USA, Article 8, 9 pages. https://doi.org/10.1145/3343036.3343139

[31] Seungwoo Je, Myung Jin Kim, Woojin Lee, Byungjoo Lee, Xing-Dong Yang, Pedro Lopes, and Andrea Bianchi. 2019. Aero-plane: A Handheld Force-Feedback Device that Renders Weight Motion Illusion on a Virtual 2D Plane. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 763–775. https://doi.org/10.1145/3332165.3347926

[32] Marc Jeannerod and Elisabeth Pacherie. 2004. Agency, Simulation and Self-identification. *Mind & Language* 19, 2 (2004), 113–146.

[33] Nadav D Kahanowich and Avishai Sintov. 2024. Learning Human-arm Reaching Motion Using a Wearable Device in Human–Robot Collaboration. *IEEE Access* 12 (2024), 24855–24865.

[34] Andreas Kalckert and HH Ehrsson. 2017. The Onset Time of the Ownership Sensation in the Moving Rubber Hand Illusion. *Frontiers in Psychology* 8 (2017), 344.

[35] Alexander Kalus, Martin Kocur, Johannes Klein, Manuel Mayer, and Niels Henze. 2023. PumpVR: Rendering the Weight of Objects and Avatars through Liquid Mass Transfer in Virtual Reality. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 263, 13 pages. https://doi.org/10.1145/3544548.3581172

[36] Shunichi Kasahara, Keina Konno, Richi Owaki, Tsubasa Nishi, Akiko Takeshita, Takayuki Ito, Shoko Kasuga, and Junichi Ushiba. 2017. Malleable Embodiment: Changing Sense of Embodiment by Spatial-Temporal Deformation of Virtual Human Body. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 6438–6448. https://doi.org/10.1145/3025453.3025962

[37] Mohamed Khamis, Nora Schuster, Ceenu George, and Max Pfeiffer. 2019. ElectroCutscenes: Realistic Haptic Feedback in Cutscenes of Virtual Reality Games Using Electric Muscle Stimulation. In *Proceedings of the 25th ACM Symposium on Virtual Reality Software and Technology* (Parramatta, NSW, Australia) *(VRST '19)*. Association for Computing Machinery, New York, NY, USA, Article 13, 10 pages. https://doi.org/10.1145/3359996.3364250

[38] Konstantina Kilteni, Raphaela Groten, and Mel Slater. 2012. The Sense of Embodiment in Virtual Reality. *Presence: Teleoperators and Virtual Environments* 21, 4 (Nov. 2012), 373–387. https://doi.org/10.1162/PRES_a_00124

[39] Jarrod Knibbe, Paul Strohmeier, Sebastian Boring, and Kasper Hornbæk. 2017. Automatic Calibration of High Density Electric Muscle Stimulation. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 3, Article 68 (sep 2017), 17 pages. https://doi.org/10.1145/3130933

[40] Heather Knight and Reid Simmons. 2016. Laban Head-motions Convey Robot State: A Call for Robot Body Language. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2881–2888.

[41] Martin Kocur, Alexander Kalus, Johanna Bogon, Niels Henze, Christian Wolff, and Valentin Schwind. 2022. The Rubber Hand Illusion in Virtual Reality and the Real World - Comparable but Different. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology* (Tsukuba, Japan) *(VRST '22)*. Association for Computing Machinery, New York, NY, USA, Article 31, 12 pages. https://doi.org/10.1145/3562939.3565614

[42] Andrey Krekhov, Sebastian Cmentowski, and Jens Krüger. 2019. The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games. In *2019 IEEE Conference on Games (CoG)*. IEEE, 1–8. https://doi.org/10.1109/CIG.2019.8848005

[43] Yosuke Kurihara, Seiya Takei, Yuriko Nakai, Taku Hachisu, Katherine J. Kuchenbecker, and Hiroyuki Kajimoto. 2014. Haptic Robotization of the Human Body by Data-Driven Vibrotactile Feedback. *Entertainment Computing* 5, 4 (Dec. 2014), 485–494. https://doi.org/10.1016/j.entcom.2014.08.010

[44] C. La Viola, L. Fiorini, G. Mancioppi, J. Kim, and F. Cavallo. 2022. Humans and Robotic Arm: Laban Movement Theory to create Emotional Connection *. In *2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)* (Napoli, Italy). IEEE Press, 566–571. https://doi.org/10.1109/RO-MAN53752.2022.9900708

[45] Marc Erich Latoschik and Carolin Wienrich. 2022. Congruence and Plausibility, not Presence: Pivotal Conditions for XR Experiences and Effects, a Novel Approach. *Frontiers in Virtual Reality* 3 (2022), 694433.

[46] Amy LaViers and Magnus Egerstedt. 2012. Style Based Robotic Motion. In *2012 American Control Conference (ACC)*. IEEE, 4327–4332. https://doi.org/10.1109/ACC.2012.6315287

[47] Amy LaViers, Lori Teague, and Magnus Egerstedt. 2014. Style-Based Robotic Motion in Contemporary Dance Performance. In *Controls and Art: Inquiries at the Intersection of the Subjective and the Objective*. Springer International Publishing, Cham, 205–229. https://doi.org/10.1007/978-3-319-03904-6_9

[48] Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. 2015. Proprioceptive Interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 939–948. https://doi.org/10.1145/2702123.2702461

[49] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1471–1482. https://doi.org/10.1145/3025453.3025600

[50] Tino Lourens, Roos van Berkel, and Emilia Barakova. 2010. Communicating Emotions and Mental States to Robots in a Real Time Parallel Framework Using Laban Movement Analysis. *Robotics and Autonomous Systems* 58, 12 (Dec. 2010), 1256–1265. https://doi.org/10.1016/j.robot.2010.08.006

[51] Azumi Maekawa, Shota Takahashi, MHD Yamen Saraiji, Sohei Wakisaka, Hiroyasu Iwata, and Masahiko Inami. 2019. Naviarm: Augmenting the Learning of Motor Skills Using a Backpack-Type Robotic Arm System. In *Proceedings of the 10th Augmented Human International Conference 2019 (AH '19)*. Association for Computing Machinery, New York, NY, USA, Article 38, 8 pages. https://doi.org/10.1145/3311823.3311849

[52] Megumi Masuda and Shohei Kato. 2010. Motion Rendering System for Emotion Expression of Human Form Robots Based on Laban Movement Analysis. In *19th International Symposium in Robot and Human Interactive Communication*. 324–329. https://doi.org/10.1109/ROMAN.2010.5598692

[53] Zachary McKendrick, Ori Fartook, Patrick Finn, Ehud Sharlin, and Jessica Cauchard. 2023. Waiting in the Wings: Drones in Live Performance. In *Graphics Interface 2023 - second deadline*.

[54] Marie Muehlhaus, Alexander Liggesmeyer, and Jürgen Steimle. 2025. ExoKit: A Toolkit for Rapid Prototyping of Interactions for Arm-based Exoskeletons. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '25)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3706598.3713815

[55] Florian 'Floyd' Mueller, Nathan Semertzidis, Josh Andres, Joe Marshall, Steve Benford, Xiang Li, Louise Matjeka, and Yash Mehta. 2023. Toward Understanding the Design of Intertwined Human–Computer Integrations. *ACM Trans. Comput.-Hum. Interact.* 30, 5, Article 73 (Sept. 2023), 45 pages. https://doi.org/10.1145/3590766

[56] Junichi Nabeshima, MHD Yamen Saraiji, and Kouta Minamizawa. 2019. Prosthetic Tail: Artificial Anthropomorphic Tail for Extending Innate Body Functions. In *Proceedings of the 10th Augmented Human International Conference 2019* (Reims, France) *(AH'19)*. Association for Computing Machinery, New York, NY, USA, Article 36, 4 pages. https://doi.org/10.1145/3311823.3311848

[57] Alexander Nguyen and Biyun Xie. 2021. Human Arm Motion Prediction in Reaching Movements. In *2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN)*. 1117–1123. https://doi.org/10.1109/RO-MAN50785.2021.9515461

[58] Jun Nishida, Yudai Tanaka, Romain Nith, and Pedro Lopes. 2022. DigituSync: A Dual-User Passive Exoskeleton Glove That Adaptively Shares Hand Gestures. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 59, 12 pages. https://doi.org/10.1145/3526113.3545630

[59] Max Pfeiffer, Tim Duente, and Michael Rohs. 2016. Let Your Body Move: A Prototyping Toolkit for Wearable Force Feedback With Electrical Muscle Stimulation. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Florence, Italy) *(MobileHCI '16)*. Association for Computing Machinery, New York, NY, USA, 418–427. https://doi.org/10.1145/2935334.2935348

[60] Max Pfeiffer, Tim Dünte, Stefan Schneegass, Florian Alt, and Michael Rohs. 2015. Cruise Control for Pedestrians: Controlling Walking Direction using Electrical Muscle Stimulation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2505–2514. https://doi.org/10.1145/2702123.2702190

[61] Mose Sakashita, Satoshi Hashizume, and Yoichi Ochiai. 2019. Wrist-Mounted Haptic Feedback for Support of Virtual Reality in Combination with Electrical Muscle Stimulation and Hanger Reflex. In *Human-Computer Interaction. Recognition and Interaction Technologies: Thematic Area, HCI 2019, Held as Part of the 21st HCI International Conference, HCII 2019, Orlando, FL, USA, July 26–31, 2019, Proceedings, Part II 21*. Springer International Publishing, Cham, 544–553. https://doi.org/10.1007/978-3-030-22643-5_43

[62] Ali-Akbar Samadani, Sarahjane Burton, Rob Gorbet, and Dana Kulic. 2013. Laban Effort and Shape Analysis of Affective Hand and Arm Movements. In *2013 Humaine Association Conference on Affective Computing and Intelligent Interaction*. 343–348.

[63] Kadek Ananta Satriadi, Andrew Cunningham, Ross T. Smith, Tim Dwyer, Adam Drogemuller, and Bruce H. Thomas. 2023. ProxSituated Visualization: An Extended Model of Situated Visualization using Proxies for Physical Referents. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 382, 20 pages.

[64] Shuto Takashita, Ken Arai, Hiroto Saito, Michiteru Kitazaki, and Masahiko Inami. 2024. Embodied Tentacle: Mapping Design to Control of Non-Analogous Body Parts with the Human Body. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 222, 19 pages. https://doi.org/10.1145/3613904.3642340

[65] Emi Tamaki, Takashi Miyaki, and Jun Rekimoto. 2011. PossessedHand: Techniques for Controlling Human Hands Using Electrical Muscles Stimuli. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 543–552. https://doi.org/10.1145/1978942.1979018

[66] Shan-Yuan Teng, K. D. Wu, Jacqueline Chen, and Pedro Lopes. 2022. Prolonging VR Haptic Experiences by Harvesting Kinetic Energy from the User. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22)*. Association for Computing Machinery, Article 39, 18 pages. https://doi.org/10.1145/3526113.3545635

[67] Vy Dang Ha Thanh, Ondris Pui, and Martin Constable. 2017. Room VR: A VR Therapy Game for Children Who Fear the Dark. In *SIGGRAPH Asia 2017 Posters*

(Bangkok, Thailand) *(SA '17)*. Association for Computing Machinery, New York, NY, USA, Article 52, 2 pages. https://doi.org/10.1145/3145690.3145734

[68] Yoji Uno, Mitsuo Kawato, and Rika Suzuki. 1989. Formation and Control of Optimal Trajectory in Human Multijoint Arm Movement. *Biological Cybernetics* 61, 2 (1989), 89–101.

[69] Karthikeya Puttur Venkatraj, Wo Meijer, Monica Perusquia-Hernandez, Gijs Huisman, and Abdallah El Ali. 2024. ShareYourReality: Investigating Haptic Feedback and Agency in Virtual Avatar Co-embodiment. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 100, 15 pages. https://doi.org/10.1145/3613904.3642425

[70] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 143–146. https://doi.org/10.1145/1978942.1978963

[71] Erik Wolf, Nina Döllinger, David Mal, Carolin Wienrich, Mario Botsch, and Marc Erich Latoschik. 2020. Body Weight Perception of Females Using Photorealistic Avatars in Virtual and Augmented Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 462–473. https://doi.org/10.1109/ISMAR50242.2020.00071

[72] Nick Yee and Jeremy Bailenson. 2007. The Proteus Effect: The Effect of Transformed Self-representation on Behavior. *Human Communication Research* 33, 3 (2007), 271–290.

[73] Andy Zelenak, Clinton Peterson, Jack Thompson, and Mitch Pryor. 2015. The Advantages of Velocity Control for Reactive Robot Motion. In *Dynamic Systems and Control Conference*, Vol. 57267. American Society of Mechanical Engineers, V003T43A003.

[74] André Zenner, Hannah Maria Kriegler, and Antonio Krüger. 2021. HaRT - The Virtual Reality Hand Redirection Toolkit. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI EA '21)*. Association for Computing Machinery, New York, NY, USA, Article 387, 7 pages. https://doi.org/10.1145/3411763.3451814