Embodied Avatar Movement Distortions in Virtual Reality: Effects on Gait Symmetry and Goal-Directed Reaching Movements of the Upper and Lower Limbs

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Distorsions des mouvements d'un avatar incarné en réalité virtuelle : effets sur la symétrie de la marche et les mouvements de portée dirigés du membre supérieur et inférieur

Iris WILLAERT

RÉSUMÉ

Dans la réalité virtuelle immersive, lorsque le suivi du corps entier est activé, un avatar peut reproduire les mouvements de l'utilisateur en vue à la première personne et ainsi servir de représentation du corps de l'utilisateur dans l'environnement virtuel. Si les mouvements de l'avatar sont suffisamment synchronisés avec ceux de l'utilisateur, ce dernier peut ressentir un sentiment d'incarnation envers l'avatar. Des études récentes ont montré que ce sentiment peut persister même lorsque les mouvements de l'avatar s'écartent spatialement de ceux de l'utilisateur. Toutefois, ces études se sont principalement concentrées sur les mouvements du membre supérieur, qui sont généralement délibérés, guidés visuellement et orientés vers un but, tandis que la marche est un comportement moteur rythmique et automatique. Il reste donc à déterminer si de telles distorsions spatiales auraient le même effet dans ce contexte. Par ailleurs, dans ces études antérieures, les mouvements de l'avatar étaient dirigés vers une cible visible, ce qui pourrait avoir contribué à l'alignement moteur observé, traduisant une réponse influencée par la cible et la structure de la tâche, plutôt qu'une tendance à suivre les mouvements déformés de l'avatar.

L'objectif principal de cette thèse est de mieux comprendre comment les distorsions spatiales appliquées à un avatar incarné influencent la tendance des individus à suivre les mouvements de l'avatar, ainsi que la manière dont le sentiment d'incarnation est affecté et modulé par ces ajustements moteurs.

Pour mieux comprendre comment la marche réagit à ces distorsions, nous avons développé un algorithme permettant de manipuler en temps réel la longueur d'un pas de l'avatar, en augmentant ou diminuant progressivement la distorsion. La première étude a évalué le seuil à partir duquel la distorsion devenait consciemment perceptible, ainsi que son impact sur le sentiment d'incarnation. Les résultats ont montré que des distorsions allant jusqu'à 12% pouvaient passer inaperçues lorsqu'elles augmentaient progressivement, tandis qu'elles n'étaient plus détectées lorsqu'elles descendaient en dessous de 9%. Le sentiment d'incarnation diminuait avec l'ampleur de la distorsion, mais n'était pas rompu par la simple détection consciente. De plus, l'incarnation pouvait être induite à des niveaux élevés de distorsion lorsqu'elle était réduite progressivement, plutôt que par la méthode traditionnelle consistant à induire l'incarnation sans distorsion avant de l'augmenter graduellement.

Une analyse secondaire des mêmes données expérimentales a examiné si les participants ajustaient leur démarche pour suivre la longueur de pas déformée de l'avatar, et si ces ajustements étaient influencés par la détection consciente ou les variations du sentiment d'incarnation. Cependant, malgré la perception de la distorsion, aucun changement de symétrie de la marche n'a été observé, ce qui suggère que la marche pourrait être résistante à la manipulation par retour visuel. En revanche, les études antérieures montrant un effet d'alignement avec un

avatar déformé concernaient généralement des mouvements discrets du membre supérieur, qui diffèrent de la marche par leur nature plus volontaire et visuellement guidée. De plus, ces études impliquaient souvent des mouvements vers des cibles visibles, laissant incertain si un alignement persisterait en l'absence de repères visuels.

Pour vérifier si les participants suivraient l'avatar dans des actions plus délibérées, sans repères visuels explicites, nous avons conçu une troisième étude portant sur des mouvements de portée du membre supérieur et inférieur réalisés sans cibles visuelles. Un algorithme a été développé pour introduire progressivement une déviation latérale dans la trajectoire de l'avatar, relative à une direction de référence droite vers l'avant, la distorsion augmentant après chaque mouvement. Contrairement à notre hypothèse, les participants ne se sont pas alignés sur la trajectoire déformée de l'avatar, mais ont activement contre-réagi à la distorsion.

Ensemble, ces résultats apportent un éclairage nouveau sur les limites de l'incarnation et les mécanismes sous-jacents à l'adaptation motrice. Ils montrent qu'un fort sentiment d'incarnation peut persister en présence de distorsions spatiales, mais que cela ne conduit pas nécessairement à un alignement comportemental avec l'avatar. Lors de la marche, les participants ont largement ignoré les distorsions, probablement en raison du caractère automatique et rythmique de la locomotion. En revanche, dans une tâche de portée dirigée, lorsque la distorsion contredisait les attentes liées au déroulement du mouvement, les participants ont activement contre-réagi.

Mots-clés: réalité virtuelle, incarnation, ego-avatars, perception, distorsion, symétrie de la marche, longueur de pas, rééducation de la marche, mouvements de pointage, contrôle moteur

Embodied Avatar Movement Distortions in Virtual Reality: Effects on Gait Symmetry and Goal-Directed Reaching Movements of the Upper and Lower Limbs

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ABSTRACT

In immersive virtual reality, when full-body tracking is enabled, a self-avatar can mimic the user's movements from a first-person perspective and can serve as a representation of the user's body within the virtual environment. If the avatar's movements are sufficiently synchronized with the user's actual movements, the user can experience a sense of embodiment over the avatar. Recent studies have shown that the sense of embodiment can persist even when the avatar is programmed to spatially deviate from the user's actual movements. While such studies have primarily focused on upper-limb movements, which are typically deliberate, visually guided, and goal-directed, gait is a rhythmic and automatic motor behavior, and it remains unclear whether spatial distortions would persist in this context. Furthermore, in these prior studies, the avatar's movements were directed toward a visible target, which may have contributed to the observed motor alignment, reflecting a response which was influenced by the goal and task structure, rather than a tendency to follow the distorted avatar's movements.

Therefore, the main objective of this thesis is to better understand how spatial distortions applied to an embodied avatar influence individuals' tendency to follow the avatar's movements, and to explore the interrelation between these distortions, motor adjustments, and the sense of embodiment.

To better understand how gait responds to these distortions, we developed an algorithm to manipulate one of the avatar's step lengths in real time by gradually increasing or decreasing the distortion. The first study assessed at which point the step length distortion became consciously noticeable and evaluated the impact of this detection on the sense of embodiment. Results showed that, on average, increasing distortions up to 12% could go undetected, while decreasing distortions were no longer noticed once they dropped below 9%. The sense of embodiment decreased with increasing distortion but was not disrupted by conscious detection alone. Furthermore, embodiment could be induced at high levels by gradually decreasing the distortion applied to an avatar, rather than the traditional method that consists of inducing embodiment without distortions and gradually applying them.

A secondary analysis of the same experimental data examined whether participants would adjust their gait to follow the avatar's distorted step length, and whether such adjustments were influenced by conscious detection or changes in embodiment. However, despite perceiving the distortion, participants showed no changes in gait symmetry, suggesting that gait may be resistant to visual feedback manipulation. In contrast, earlier studies reporting an effect where participant align their movements with their distorted avatars typically involved discrete upper-limb movements, which differ from gait in being less automatic and more visually guided. Moreover, as those previous studies typically involved reaching movements toward visible targets, it remained unclear whether participants would align with a distorted avatar in the absence of such visual cues.

To verify whether participants would follow the avatar in more deliberate actions without explicit visual guidance, we designed a third study focusing on upper and lower-limb reaching movements performed without visual targets. An algorithm was developed that progressively increased the avatar's lateral deviation relative to a fixed straight-ahead reference, with the magnitude of distortion increasing gradually after each reach. Contrary to our hypothesis, participants did not align their movements with the avatar's distorted reaching trajectory but instead actively counteracted the distortion.

Together, these findings provide new insights into the boundaries of embodiment and the mechanisms supporting motor adaptation. They demonstrate that a strong sense of embodiment can persist even in the presence of spatial distortions, but that this does not necessarily lead to behavioral motor alignment with the avatar. During gait, participants largely disregarded the spatial distortions, likely due to the automatic and rhythmical nature of walking. In contrast, during a goal-directed reaching task, when distortions conflicted with expectations about how a movement should unfold, participants actively counteracted them.

Keywords: virtual reality, embodiment, self-avatars, perception, distortion, gait symmetry, step length, gait rehabilitation, reaching movements, motor control

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LIST OF ALGORITHMS

LIST OF ABBREVIATIONS

VR	Virtual Reality
VE	Virtual environment
HMD	Head-Mounted Display
SoE	Sense of Embodiment
RHI	Rubber hand illusion
RFI	Rubber foot illusion
1PP	First-person perspective
3PP	Third-person perspective
ROM	Range of motion
AP	Anterior-Posterior
ML	Medio-Lateral
IK	Inverse Kinematics
CoP	Center of Pressure
CoM	Center of Mass

INTRODUCTION

In immersive virtual reality, users typically do not see their physical bodies within the virtual environment. However, through full-body tracking, they can instead perceive themselves as self-avatars, digital representations of their bodies in the virtual space. When displayed from a first-person perspective, these avatars act as substitutes for the user's physical body, making the otherwise invisible body visible within the virtual world.

When the movements of the avatar are sufficiently synchronized with the user's real-world movements, this alignment often creates a sense of embodiment, the subjective experience of owning and controlling the virtual body (Kilteni & Slater, 2012). This phenomenon arises from the integration of multisensory inputs, including visual, proprioceptive, and motor feedback. When these signal are coherent with the user's actions can lead to the attribution of the virtual avatar as part of the user's body (Slater *et al.*, 2009).

However, recent research has shown that the sense of embodiment can be maintained even when a degree of spatial misalignment is introduced between the user's and the avatar's movements (Porssut *et al.*, 2022a, 2019; Galvan Debarba *et al.*, 2018; Bovet *et al.*, 2018). Moreover, such spatial distortions have been shown not only to preserve the sense of embodiment, but also to alter body perception.

In static conditions, such effects have been widely demonstrated through proprioceptive drift, a shift in the perceived position of one's limb towards a visually displaced body part. This has been illustrated with the rubber hand illusion, participants view a fake hand being stroked while their hidden real hand receives synchronous tactile stimulation, resulting in a perceptual shift of the real hand's position toward the fake hand (Botvinick & Cohen, 1998). Furthermore, when the real hand is placed on a movable platform, it has been shown to physically drift toward the fake hand, indicating that not only a perceived shift is observed but also an actual displacement of the limb's physical position (Asai, 2014). More recently, it was found that participants exerted involuntary forces in the direction of the displaced fake limb (Lanillos *et al.*, 2021). These perceptual and motor responses are thought to arise from the brain's attempt to resolve multisensory discrepancies caused by conflicting visual, proprioceptive, and tactile input (Lanillos *et al.*, 2021; Asai, 2014).

In dynamic conditions, where participants are able to control the movements of their avatar, these spatial distortions have also been shown to influence movement execution in some specific tasks involving the upper limb. For example, during a drawing task, when the avatar's hand deviated from a straight-line path, participants unconsciously altered their drawing trajectory, producing oval-shaped lines instead (Burin *et al.*, 2019). Similarly, in a goal-directed reaching task, when the avatar's hand was snapped to a predefined trajectory, participants unknowingly adjusted their movements to align more closely with the avatar's, despite not being explicitly instructed to do so (Cohn *et al.*, 2020a; Gonzalez-Franco *et al.*, 2020). Maselli *et al.* (2022) further showed that when a velocity gain was applied to the avatar's hand, causing it to reach the target before the user's real hand, participants adapted by increasing their movement speed to match the virtual hand.

While these findings highlight that spatial distortions can affect motor behavior in certain upper-limb tasks, such as reaching or drawing, which rely more heavily on visual feedback, it remains unclear how healthy individuals respond to such distortions during more automatic, less visually dependent movements, such as gait. Furthermore, these previous studies often included a visible target, meaning that the avatar's altered movements were always oriented toward an explicit goal (Cohn *et al.*, 2020a; Gonzalez-Franco *et al.*, 2020; Maselli *et al.*, 2022). Therefore, although motor adjustments were observed, it remains unclear whether these reflected a tendency to follow the avatar or were driven by the goal-directed nature of the task.

To address these gaps, the primary objective of this thesis is to better understand how spatial distortions applied to an embodied avatar affect individuals' tendency to follow the avatar's movements, and how the sense of embodiment interrelates with both the distortion and the resulting motor adjustments.

To investigate how spatial distortions affect motor behavior during gait, it is necessary to examine individuals' sensitivity to spatial mismatches and how conscious awareness of these distortions impacts their sense of embodiment. By identifying the levels at which distortions are perceived and how strongly they affect embodiment, we can explore whether these factors might influence individuals' tendency to adjust their walking patterns to align with the avatar, and what role the sense of embodiment plays in this process. This sensitivity can be obtained using a detection threshold, the level of spatial distortion below which users are unaware of the misalignment between their movements and the avatar's.

To explore this, a first study was designed to examine the relationship between the amplitude of the step length distortion, the detection threshold, and the perceived sense of embodiment during gait. An algorithm was developed to unilaterally gradually increase the step length of an embodied avatar in real-time. Two conditions were employed: an ascending approach, in which distortions were gradually increased, and a descending approach, where a large, clearly noticeable distortion was introduced at the start and then progressively reduced. This descending protocol allowed for the evaluation of the point at which a previously detected distortion is no longer perceived as misaligned and instead begins to be experienced as part of one's own body. In other words, is reducing the distortion until it falls below the detection threshold sufficient to restore embodiment, or is a complete recalibration (returning to perfect alignment) required first? To date, this descending approach has not been explored, and no prior studies have applied either ascending or descending protocols in the context of gait, where embodiment processes and sensory integration may differ from those observed in upper-limb tasks due to the distinct nature of gait.

The second study examined whether step length distortions would lead to motor adjustments and induce gait asymmetry. To our knowledge, no previous studies have investigated the relationship between distortion detection thresholds, the sense of embodiment, and the tendency to adjust one's movements to follow a distorted avatar trajectory. Specifically, this study assessed whether participants altered their step length to align with their distorted avatar's movements, and whether such adjustments persisted after the conscious detection of the distortion or if a minimum level of embodiment is necessary to sustain such adjustments.

However, the results from this second study revealed that the applied step length distortions had no observable effect on gait symmetry. This lack of adaptation could be attributed to the specific characteristics of gait (Malone & Bastian, 2010; Clark, 2015), which contrast with the goal-directed and visually guided nature of the upper-limb tasks studied previously (Cohn *et al.*, 2020a; Gonzalez-Franco *et al.*, 2020; Maselli *et al.*, 2022). Gait primarily involves the lower limbs, which are specialized for locomotion and postural control, unlike the upper limbs, which are optimized for dexterous tasks requiring fine motor control.

Moreover, given that those prior studies often involved goal-directed reaching movements toward an explicit target, potentially prompting alignment with the avatar because of the structure of the task itself, it remains unclear whether the observed tendency to follow the avatar would occur in the absence of such visual goals.

Consequently, a third study was designed to further investigate how users adapt to movements to the distortion of their embodied avatar during goal-directed reaching movements of the upper and lower limbs when no visual targets are present. To implement this, an algorithm was developed which gradually introduced spatial distortions to the avatar's trajectory by incrementally deviating its movement laterally relative to a fixed straight-ahead reference direction. The removal of the target introduced a visuomotor ambiguity, requiring participants to reconcile discrepancies between the visual representation of the avatar's limb and their own proprioceptive feedback.

This approach allows us to study whether participants align their movements with the avatar's distorted trajectory during reaching movements in the absence of an explicit visual target. In addition, to examine whether postural demands might influence participants' sensitivity to spatial distortions, we included a condition in which lower-limb reaching movements were performed while balancing on one foot without external support, thereby increasing stability demands.

Together, these three studies contribute to a deeper understanding of how spatial distortions applied to an embodied avatar influence both motor behavior and the sense of embodiment. Specifically, they investigate how such distortions affect gait symmetry during locomotor tasks, and how they influence goal-directed upper- and lower-limb reaching in the absence of visual targets.

The remainder of this thesis is structured as follows. CHAPTER 1 provides a literature review on the sense of embodiment in virtual environments, how distortions applied to embodied avatars can affect motor behaviour and the role of visual feedback on gait and motor control during reaching movements of the upper and lower limb. CHAPTER 2 presents the objectives and hypotheses of this thesis. CHAPTER 3 details the methods and materials used for all three studies, including the development of the virtual environment along with the algorithms used to manipulate the avatar's step length and introduce spatial distortions during reaching tasks of the upper and lower limbs.

CHAPTER 4 presents the first study, which establishes the detection threshold for step length asymmetry and examines its relationship with conscious detection and the sense of embodiment. This study was published in *Frontiers in Virtual Reality*. In CHAPTER 5, the effects of avatar-induced distortions on gait symmetry were analyzed. The second study was submitted for publication to *IEEE Transactions on Visualization and Computer Graphics* and is currently under review. CHAPTER 6 examines the effect of applying spatial distortion to an embodied avatar during goal-directed upper and lower-limb voluntary reaching movements when no visual target is provided. The third study was submitted for publication to *IEEE Transactions on Visualization and Computer Graphics* and is currently under review.

Finally, CHAPTER 7 provides a general discussion of the findings, placing them in the context of the initial hypotheses and existing literature, and outlines potential applications and directions for future research.

CHAPTER 1

LITERATURE REVIEW

This chapter presents a review of the literature on the sense of embodiment in immersive virtual environments, the influence of embodied avatars on motor performance, and the effects of visual feedback on gait parameters and goal-directed reaching with the upper and lower limbs.

1.1 Immersive virtual reality

Virtual reality (VR) enables users to be fully immersed in a simulated 3D computer-generated virtual environment, which can either resemble the real physical world or represent entirely imagined and abstract spaces. Virtual environments are commonly displayed through head-mounted displays (HMDs), which provide users with an engaging and interactive experience by enabling direct interaction with their surroundings.

The increasing accessibility and affordability of VR technology have established its status as a powerful tool for experimental research. Immersive VR environments provide researchers with the unique ability to investigate complex aspects of human behavior and physiology, including motor control, sensory integration, cognitive processes, and social interactions, all within a safe and ecologically valid setting (Parsons, 2015). With precise control over stimuli and the ability to manipulate variables in real time, VR offers opportunities for conducting reproducible and highly customizable experimental studies (Rizzo *et al.*, 2001).

Modern advancements in VR now allow for the integration of multimodal sensory inputs, including visual, auditory and haptic stimuli. This multimodal interaction significantly enhances the sense of immersion, enabling researchers to design experiments that would be difficult or impossible to conduct in the real physical world (Bohil *et al.*, 2011).

The following section explores the components and mechanisms underlying the Sense of Embodiment and its implications for virtual reality research.

1.2 The sense of embodiment

What does it mean to own, control, and exist within a body? Cognitive science has long explored these fundamental questions to better understand how humans experience themselves within a body that interacts with the environment. Humans experience themselves as being inside a body that moves according to their intentions. This sense of being "inside" a body that moves according to one's intentions reflects the interconnected relationship between the body and mind, a phenomenon referred to as embodiment.

Within VR environments, embodiment has been described as the subjective experience of being inside a virtual body. It plays a critical role in enabling a sense of presence, or the feeling of "being there" within a virtual environment (Sanchez-Vives & Slater, 2005). This immersive experience is crucial for creating realistic and engaging VR applications (Slater *et al.*, 2009).

Kilteni & Slater (2012) introduced the term Sense of Embodiment (SoE) to describe the experience of the feeling of being inside, having and controlling a virtual body as one's own. They divided the SoE in three core subcomponents that contribute to this subjective experience:

1. Sense of Body Ownership: The sensation of owning the virtual body.
2. Sense of Self-Location: The perception of being located with the virtual body.
3. Sense of Agency: The feeling of having global motor control, where one can intentionally initiate and control actions performed by the virtual body.

Together, these subcomponents form a cohesive sense of embodiment, allowing users to experience the virtual body as an extension of their own physical self.

1.2.1 The sense of ownership

Body ownership refers to one's self-attribution of a body as their own (Tsakiris, 2010). Humans normally know precisely what belongs to their own bodies and what belongs to the external world around them. However, the Rubber Hand Illusion (RHI), first described by Botvinick and Cohen (1998), demonstrated that the sense of body ownership can be experimentally manipulated. By synchronously tapping and stroking a participant's hidden real hand and a spatially aligned rubber hand, participants temporarily experience an illusory sense of ownership over the rubber hand (Botvinick & Cohen, 1998). Participant report that they perceive their own hand at the location shifted towards the seen position of the rubber hand, provided that the rubber hand is placed in an anatomically plausible position compared to the real hand (Tsakiris & Haggard, 2005).

The RHI arises through multisensory integration, where the brain combines visual, tactile, and proprioceptive information to create a coherent body representation. During the RHI, the real hand is hidden, and its proprioceptive position (where the hand is physically sensed to be) does not align with the visual input (the visible rubber hand). This creates a mismatch between where the brain expects the hand to be based on proprioception and what it perceives visually. When the rubber hand is stroked in synchronization with the hidden real hand, the brain receives congruent tactile information on the real hand while visually observing the rubber hand. The brain resolves this sensory ambiguity by attributing the tactile sensations to the rubber hand, resulting in a temporary sense of ownership over the rubber hand.

Conversely, temporal asynchronous stimulation (visible strokes on the rubber hand are temporality do not align with the tactile sensation on the real hand) significantly diminishes the illusion strength or entirely prevents the illusion from happening (Costantini *et al.*, 2016). The RHI highlights the flexibility of the brain's body schema, demonstrating how temporal congruence can significantly alter one's perception of self and body ownership. Additionally, spatial factors play a crucial role, as misalignment between the real and rubber hand beyond certain limits (reported distance up to 30 cm) can also reduce or eliminate the illusion (Lloyd, 2007; Preston, 2013; Kalckert & Ehrsson, 2014).

The RHI has been demonstrated to take place in other body parts, such as the feet, through a phenomenon known as the Rubber Foot Illusion (RFI). In this paradigm, synchronous visuotactile stimulation applied to a rubber foot and a hidden real foot induces an illusory sense of ownership over the rubber foot (Crea *et al.*, 2015; Flögel *et al.*, 2016; Lenggenhager *et al.*, 2015). Studies have shown that the RFI can be elicited with comparable strengths to the RHI (Flögel *et al.*, 2016), further supporting the role of multisensory integration in generating the illusion. As observed in the RHI, the illusion is significantly diminished or absent when visuotactile stimulation is asynchronous (Flögel *et al.*, 2016; Crea *et al.*, 2015).

In virtual environments, body ownership has been studied using the "Virtual Arm Illusion," where participants can experience ownership over a virtual limb when visuotactile stimulation is applied synchronously to their hidden real hand and the spatially aligned virtual hand (Slater *et al.*, 2008). Similar effects have been observed in the lower limbs, where participants experienced ownership over virtual legs under conditions of visuotactile synchrony (Pozeg *et al.*, 2015).

Beyond limb ownership, full-body ownership can also be induced, allowing participants to perceive a virtual avatar of themselves as their own body (Slater *et al.*, 2010). As in limb ownership paradigms, the full-body illusion occurs through the integration of multisensory cues, combining visual, tactile, and proprioceptive inputs to create a coherent representation of the body. When visuotactile synchrony (touch on the real body corresponding with seen touch on the avatar) or visuomotor synchrony (real movements mapped onto the avatar) are present, participants are more likely to experience the avatar as their own body (Lenggenhager *et al.*, 2007).

While the sense of ownership plays a crucial role in shaping the full-body illusion, self-location, the feeling of where one is in space, and the sense of agency, the feeling of control over one's body also contributes to generating the sense of embodiment in virtual reality. These aspects are explored in more detail in the following subsections.

1.2.2 The sense of self-location

The sense of self-location refers to the subjective experience of being spatially situated inside a body (Kilteni & Slater, 2012). In a virtual environment, the spatial alignment of the avatar with the user's physical body plays a crucial role in enabling the sense of embodiment. When a virtual body is experienced from a first-person perspective (1PP), substituting for the real, hidden body, users can experience a strong sense of self-location within the avatar. This alignment reinforces the feeling that one's self is situated inside the virtual body, enhancing the overall sense of embodiment.

Slater *et al.* (2010) demonstrated that a 1PP is critical for inducing a sense of self-location and ownership in virtual environments. When participants viewed a virtual body from 1PP, replacing their real body, they experienced a strong illusion of embodiment. While synchronous tactile stimulation (e.g., stroking both the real and virtual bodies simultaneously) further strengthened the illusion by aligning visual and tactile inputs, 1PP alone was sufficient to generate a strong sense of ownership and self-location. This may be explained by the virtual body being perceived in the same spatial location as where the real body should be. In contrast, when the stroking was asynchronous, the sense of self-location and ownership significantly diminished. This highlights the importance of both visual perspective and multisensory congruence in generating a coherent sense of self in virtual reality.

Although 1PP is a significant factor in determining self-location, it can be experimentally manipulated. This manipulation can lead to out-of-body experiences, where an individual perceives their self-location as being outside their physical body.

Lenggenhager *et al.* (2007) induced an out-of-body-like experience by placing participants in a third-person perspective (3pp), viewing their own virtual body positioned in front of them. At the same time, they felt tactile stimulation on their real back while seeing their virtual body being stroked in real-time. This setup caused many participants to mislocalize themselves towards the virtual body. However, asynchronous stroking significantly reduced this illusion, indicating that temporal congruence between seen and felt touch is crucial for altering self-location.

Interestingly, even when participants experience the avatar from a 1PP, spatial misalignments between the real and virtual body can still induce a sense of self-location. Maselli & Slater (2014) found that when the virtual body was laterally offset by 25 cm, participants maintained a sense of ownership, although diminished. However, larger misalignments (e.g., 80 cm) significantly diminished body ownership, as the virtual body was no longer aligned with the expected proprioceptive position of the real body. In contrast, self-location was more resilient, with participants still feeling positioned near the virtual body, even when ownership diminished.

Later research directly compared the effects of perspective (1PP vs. 3PP) on self-location and embodiment. Gorisse *et al.* (2017) found that self-location is strongest in 1PP, where users feel spatially situated inside the avatar. In contrast, in 3PP, users typically perceive themselves as external observers, leading to weaker embodiment. However, 3PP can still induce some level of embodiment if visuomotor synchrony (real and virtual movements matching) is preserved. Despite this, the sense of self-location remains significantly diminished compared to 1PP, reinforcing the important role of first-person visual perspective in associating the self with the virtual body.

1.2.3 The sense of agency

The sense of agency refers to the subjective experience of controlling one's actions. It involves the feeling of initiating, executing, and controlling voluntary movements, as well as the conscious experience of will and intention (Kilteni & Slater, 2012). The sense of agency is thought to arise from the brain's comparison of the predicted sensory outcomes of an action with the actual sensory feedback received. When these predictions align with the actual sensory consequences, such as during synchronous visuomotor correlations where observed and performed movements are congruent, the action is interpreted as self-generated (David *et al.*, 2008).

In the RHI paradigm the sense of agency has been explored with the moving rubber hand illusion. This demonstrated that visuomotor synchrony, where the movement of a real hand is mirrored by a virtual hand, can induce both a sense of ownership and agency over the virtual hand (Slater *et al.*, 2009). They proposed that active movement could enhance the sense of agency, which in turn might strengthen the ownership illusion. This is because actively moving and seeing the corresponding movements in the virtual limb provides a strong, congruent sensory feedback, reinforcing the integration of the virtual limb into its body schema.

Within immersive VR, visuomotor synchrony between the user's real movements and the corresponding movements of their avatar can induce a strong sense of agency over the avatar. This real-time alignment reinforces the user's feeling of "being in control", enhancing the overall sense of embodiment within the virtual environment (Kokkinara & Slater, 2014). However, when visuomotor synchrony is disrupted, such as by replacing the user's movements with a prerecorded animation, the sense of agency is significantly diminished. This disruption arises because the mismatch between the user's motor intentions and the avatar's movements causes a disruption between action and sensory feedback, leading to the attribution of the action to an external source rather than the self.

This real-time synchronization is particularly sensitive to temporal delays, also referred to as latency, which is defined as the time lag between movement execution and the corresponding visual feedback. These delays have been shown to significantly reduce the sense of agency by diminishing the feeling of control over the avatar's movements. Kannape & Blanke (2013) demonstrated that when participants walked on a treadmill while viewing their avatar from a 3PP, their sense of agency was preserved for small temporal delays. However, when the delay exceeded approximately 210 ms, participants no longer felt in control of the avatar's movements, resulting in a significant disruption of the sense of agency.

Spatial congruency is another critical factor influencing the sense of agency. (Kannape *et al.*, 2010) found that angular deviations in an avatar's walking trajectory negatively affected agency. In their study, participants walked overground in a motion capture area toward virtual targets, while their real-time movements were tracked and displayed on a large back-projection screen. Participants viewed their avatar from a 3PP as the avatar's walking trajectory was deviated by 5°, 10°, 15°, or 30° laterally to the left or right (relative to the participant's intended straight-line path toward the target). Small deviations (10°) were tolerated, but larger deviations (30°) significantly diminished the sense of agency, with participants no longer perceiving the avatar's movements as self-generated.

Even in cases where users do not physically execute a movement, visuomotor synchrony can induce an illusory sense of agency over an avatar. (Kokkinara *et al.*, 2016) demonstrated this by having participants remain seated while observing a virtual avatar walking. When the avatar was experienced from a 1PP and its head movements matched those of the participant, a strong sense of agency was reported, despite participants not physically walking. This visuomotor congruency between the real and the avatar's head movements enhanced the feeling of agency, even though the walking motion itself was not user-generated. However, in the asynchronous condition, where the avatar's movements did not match those of the participant, the reported sense of agency was significantly reduced.

Violations of agency can occur when abrupt, unexpected movements are introduced or when the avatar performs actions that contradict the user's intended movements. Such violations disrupt the user's sense of voluntary control and can diminish the overall sense of embodiment. (Padrao *et al.*, 2016) investigated these violations by manipulating avatar movements during a reaction-time task. In certain trials, the virtual hand suddenly moved in the opposite direction to the participant's intended movement. This abrupt visuomotor mismatch led to a disruption of agency. However, ownership proved more resilient to this manipulation and persisted even when agency was disrupted. However, when visuomotor congruency was restored, the sense of agency was also re-established.

Together, these findings demonstrate that minimizing latency and maintaining visuomotor congruency is crucial to enable a strong sense of agency, ultimately enhancing the user's sense of embodiment in virtual environments.

1.2.4 Multisensory integration

Within virtual environments, the SoE is achieved through multisensory integration where sensory inputs such as vision, touch, and proprioception combine to create a cohesive perception of the virtual body as one's own (Kilteni & Slater, 2012). This integration allows users to feel 'inside' the virtual body, control its movements, and experience it as their own physical self.

Several factors contribute to effectively inducing and sustaining the SoE. When a user wears an HMD, the virtual body can be experienced from a first-person perspective. This perspective allows the user to perceive the virtual body as an extension of their own and enhances the sense of self-location. Additionally, full-body tracking allows users to control the avatar's movements, further strengthening the illusion of embodiment. The visuomotor congruency, defined as the temporal and spatial alignment between the user's physical movements and the corresponding movements of the virtual avatar, plays a key role in generating the SoE (Kokkinara & Slater, 2014).

When users observe their actions mirrored in real-time by the avatar, with minimal delay and spatial misalignment, it reinforces a sense of agency and ownership over the virtual body. Similarly, visuotactile synchrony, where users simultaneously see and feel touch on the same location of the virtual body, further strengthens the sense of ownership, although it contributes less to the illusion compared to visuomotor stimulation (Kokkinara & Slater, 2014).

Numerous studies have demonstrated that the subjective feeling of embodiment in VR is highly robust and capable of producing convincing illusions. These illusions have been successfully induced in avatars with diverse characteristics, including different body sizes (Abtahi *et al.*, 2019; Banakou *et al.*, 2013), body shapes (Kilteni *et al.*, 2012; Normand *et al.*, 2011), genders (Bolt *et al.*, 2021), and races (Peck *et al.*, 2013; Banakou *et al.*, 2016).

For instance, embodying the body of a child has been shown to elicit high levels of ownership and lead to the overestimation of object sizes in virtual environments (Banakou *et al.*, 2013). This altered perception of size also affected participants' performance in a movement execution time task, where they were asked to quickly categorize presented objects as either large or small by pressing a corresponding button. When embodied in the child's body, participants exhibited slower reaction times compared to when embodied in an adult body. The authors suggested that the overestimation occurred as the brain recalibrated its spatial and size perception to match the new, smaller body, causing the virtual objects to be perceived as larger relative to the child avatar's reduced body proportions.

Slower movement execution times were similarly observed when altering the visual appearance of a virtual limb (Buetler *et al.*, 2022). Specifically, when participants embodied an arm with a stone-like appearance, they experienced a subjective sense of heaviness and reduced agility and increased heaviness, despite no changes to the physical movement constraints. In the task, participants were instructed to reach as quickly as possible from a resting position to vertically appearing spheres, and execution times were significantly slower. While the sense of ownership remained unaffected by the stone-like appearance of the virtual arm, agency was reduced, as participants reported feeling less in control of their movements. The stone-like visual representation created a strong illusion of increased weight and resistance, leading participants to perceive their arm as more difficult to move.

The altered appearance of an embodied avatar has also been demonstrated to affect gait patterns. Walking with virtual high heels was found to alter gait while participants were physically walking barefoot on a treadmill (Oberdörfer *et al.*, 2024). Participants embodying avatars wearing high heels demonstrated shorter stride lengths and increased knee flexion at heel strike in both legs, along with asymmetrical increases in hip flexion—specifically at right toe-off and left heel strike. These changes occurred despite the absence of physical footwear, indicating a visually induced adaptation of gait. The authors attributed these changes to a visually induced adaptation of gait, suggesting that participants unconsciously adjusted their walking style to match the postural and balance demands typically associated with wearing high heels, even in the absence of physical footwear. This behavior reflects the Proteus effect, where the visual characteristics of the virtual body influence the user's movements and motor strategies (Yee & Bailenson, 2007).

Even avatars with distorted bodily features, such as an unnaturally long arm, have been shown to be successfully integrated into one's body schema. In one study, participants were tasked with reaching for objects while their virtual arm was gradually extended to double its normal length (Kilteni *et al.*, 2012). Despite this unnaturally elongation of the virtual arm, a strong sense of ownership and agency was reported, provided that sensory feedback remained congruent. Furthermore, they adapted to the new arm length and successfully interacted with objects, demonstrating the plasticity of the body schema in integrating impossible bodily features.

Such body morphological distortions have been applied to the lower limb (Vallageas *et al.*, 2024). Participants embodied an avatar with a unilaterally enlarged shank during a gait initiation task and reported high levels of embodiment despite the altered proportions of their leg. Participants also perceived their enlarged leg as heavier, however, the visual altered appearance of the leg did not significantly impact gait preparation or dynamic stability during gait initiation. These findings suggest that while visual and perceptual changes influenced body representation, they did not translate into measurable biomechanical effects on movement.

Overall, these findings highlight the adaptability of the body schema in virtual environments, demonstrating how multisensory integration can induce strong embodiment illusions that can significantly affect self-perception and motor performance.

1.2.5 Proprioceptive drift

A common phenomenon observed during paradigms such as the rubber hand illusion (RHI) is proprioceptive drift. Proprioceptive drift refers to the shift in an individual's perceived location of their real hand toward a fake or virtual hand when visuotactile stimulations are applied (synchronous tapping or stroking of both the real and artificial hands)(Botvinick & Cohen, 1998). This proprioceptive drift is typically measured by asking participants to point with their contralateral hand to the perceived position of their stimulated hand with their eyes closed. When doing so, their estimate is biased toward the location of the artificial hand.

This proprioceptive drift has been shown to be strongly dependent on the synchronous visuotactile stimulation. When the rubber hand and real hand are tapped asynchronously, the RHI is typically diminished or does not occur (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005; Rohde *et al.*, 2011).

Later, Fuchs *et al.* (2016) proposed that the proprioceptive drift may not reflect a shift solely in the perceived position of the real hand toward the artificial rubber hand. Instead, their findings suggest that the perceived positions of both the real and rubber hands shift toward one another, converging at an intermediate location. This interpretation supports the idea that this drift reflects a compromise between visual and proprioceptive inputs, where neither modality fully dominates, consistent with principles of multisensory integration.

Although proprioceptive drift is often described as a perceptual recalibration, evidence suggests it also involves subtle motor adjustments. Asai (2014) demonstrated that participants involuntarily moved their real hand toward the rubber hand when their hand rested on a movable board during synchronous visuotactile stimulation. When the platform was mechanically fixed, no physical displacement occurred, but force sensors detected small lateral forces applied by the hand in the direction of the rubber hand. The author interpreted this as an implicit motor response, an unconscious attempt to reduce the conflict between visual and proprioceptive inputs, suggesting that the illusion engages the motor system even in the absence of any observable movement.

Building on this idea of motor engagement during embodiment illusions, Lanillos *et al.* (2021) extended the investigation to a virtual hand illusion. In their study, participants viewed a virtual hand offset from their real hand while resting on a robotic device equipped with a force-torque sensor. Participants experienced a sense of ownership over the virtual hand and exerted small lateral forces in the direction of the virtual hand, with the magnitude of these forces increasing as the visual-proprioceptive conflict increased. These results support the notion that the motor system actively participates in resolving multisensory discrepancies, not simply as a passive response but as part of an active inference process, where the brain generates subtle actions to minimize prediction errors and maintain a coherent body representation.

While proprioceptive drift has been most extensively studied in the context of the hand, similar effects have been observed in other body parts. In the rubber foot illusion (RFI), participants perceive the position of their real foot toward a rubber foot, with the strength of this drift being comparable to that observed in the hand (Flögel *et al.*, 2016). Moreover, in the moving rubber foot illusion, where the rubber foot moves synchronously with the participant's real foot, drift toward the rubber foot is often more pronounced compared to when the illusion is induced during static conditions (Teaford *et al.*, 2021).

Proprioceptive drift is not limited to realistic limb proportions but can also occur when visual feedback presents an unrealistic or exaggerated body representation. In the "Very Long Arm Illusion," Kilteni *et al.* (2012) demonstrated that participants controlling a virtual hand placed far beyond their real hand's physical reach experienced proprioceptive drift toward the virtual hand, as if their arm had physically lengthened to match the visual feedback. Participants felt their arm extending into virtual space, and the magnitude of drift correlated with the strength of the ownership illusion, suggesting that vision can override proprioceptive constraints, even when body proportions are distorted.

Similarly, Ogawa *et al.* (2020) showed that proprioceptive drift occurs even when the virtual hand is spatially displaced from the real hand, with greater drift observed when the virtual hand appeared realistic compared to an abstract avatar. This finding highlights that the degree of drift is not only influenced by spatial factors but also by how natural the virtual limb appears.

1.3 Movement distortion in embodied avatars

1.3.1 Detection threshold for distortion in embodied avatars

The three subcomponents of embodiment (body ownership, agency, and self-location) are essential for establishing and maintaining the illusion of embodiment (Kilteni & Slater, 2012). If any of these components are violated, the illusion can be disrupted, leading to a loss of the SoE even after it has been successfully established. Kokkinara & Slater (2014) referred to these disruptions as "breaks" in the illusion. A break occurs when participants transition from experiencing the virtual body as their own ("illusion state") to perceiving it as solely a virtual representation unrelated to their real body ("no illusion state"). They introduced a real-time method for measuring these breaks by having participants verbally report whenever they experienced a disruption in the illusion.

However, research has shown that spatial distortion applied to an avatar's movements can be tolerated without causing a break in the illusion (Burin *et al.*, 2019; Bourdin *et al.*, 2019; Porssut *et al.*, 2019). Studies were able to identify a detection threshold, below which participant did not perceive the discrepancies between their actual and the avatar's movements and the impact this threshold had on the SoE.

For instance, Kokkinara *et al.* (2015) showed that participants could accept spatial distortions of up to 11 and 22 degrees angular offset at the shoulder during reaching movements with the arm fully extended. In this setup, participants reached straight ahead with their real arm, but the virtual hand was displayed at an angular deviation from their actual arm trajectory, rotated laterally around the shoulder joint in the horizontal plane. While participants moved their hand forward, the avatar's hand appeared to follow a straight path angled 11° or 22° to the left or right of the actual direction. Despite this spatial mismatch, participants reported high levels of body ownership and agency. However, when the temporal distortions were introduced, such as increasing movement velocity to twice or four times the normal speed, participants consciously detected the mismatch, leading to a significant decrease in agency, while body ownership remained unaffected.

Porssut *et al.* (2019) applied a gradually increasing spatial distortion between the real and avatar arm position during a target-following task. In this context, spatial distortion referred to a progressive positional offset between the real hand and the avatar's hand, introduced along the movement path. The avatar's hand was displayed at a location that deviated from the actual hand position by a fixed percentage of the distance to the target. An inverse relationship was observed: ownership and agency scores decreased as the magnitude of this distortion increased. Ownership and agency were assessed through questionnaires completed after each distortion level. The authors identified a critical threshold at 60% deviation, meaning the avatar's hand appeared 60% of the way between the real hand and the target. Beyond this point, participants became consciously aware of the discrepancy. Nevertheless, many still reported a sense of embodiment at moderate levels, although high distortions ultimately led to a break in embodiment.

Furthermore, under certain conditions, detection thresholds can be extended. If the spatial distortions are deliberately designed to assist participants in completing a particularly challenging task, the SoE can be maintained beyond the detection threshold (Galvan Debarba *et al.*, 2018; Porssut *et al.*, 2019, 2022a; Delahaye *et al.*, 2023).

Another study emphasized the importance of maintaining visuotactile congruency when applying spatial distortion. In particular, incongruent feedback, such as a mismatched self-contact, was shown to significantly disrupt body ownership and agency (Bovet *et al.*, 2018). They also examined the effects of movement amplification, where the avatar's hand moved with a greater amplitude than the participant's real hand when reaching for different targets. Interestingly, this distortion did not cause a break in the SoE, as long as self-contact was preserved.

Furthermore, discrepancies between proprioceptive feedback and the expected sensory feedback from the avatar's position can break embodiment (Porssut *et al.*, 2022a). For example, in a reaching task where the avatar's arm continued moving after the participant's real arm had reached full extension, participants experienced a break in embodiment.

The extent of the disruption depends on the degree and direction of the mismatch. Negative distortions, where the avatar's arm underextends relative to the real arm, were less tolerated and significantly disrupted embodiment. In contrast, positive distortions, where the avatar's arm overextends, had a higher detection threshold and did not disrupt embodiment. This difference likely arises because positive distortions allow the avatar to reach the target even when the real arm has reached its physical limit. However, when participants reached their articular limit while the avatar's arm continued moving, the mismatch became noticeable, ultimately leading to a break in embodiment.

Detection thresholds have been predominantly investigated during upper limb movements, with limited research focusing on the lower limbs. However, a detection threshold for temporal distortions during gait has been reported in the context of a full-body avatar (Kannape & Blanke, 2013). In this study, participants walked on a treadmill while observing a full-body avatar replicating their movements in real time, displayed from a third-person perspective on a large screen positioned in front of them. The findings revealed that participants could tolerate temporal distortions of up to 210ms on average before detecting a mismatch. Additionally, the sense of agency gradually decreased as the temporal distortion increased, rather than showing a sudden break at the detection threshold.

1.3.2 Impact of embodied avatar distortions on motor performance

Some recent evidence suggests that when applying embodied distortions, participant are influenced by the movements of their distorted avatars, unconsciously adjusting their own movements to align more closely with the avatar's. Gonzalez-Franco *et al.* (2020) investigated this effect by instructing participants to perform reaching movements between two visual targets positioned along the antero-posterior axis of the shoulder joint. However, the avatar's arm followed a predefined trajectory, introducing a spatial offset that caused it to deviate laterally from a straight trajectory.

To examine the effect of the distortion, two conditions were introduced. In the gradual condition, the spatial offset increased by one degree with each reach, eventually reaching a maximum of 30 degrees. In the instantaneous condition, the avatar's trajectory was immediately offset by 30 degrees at the start of the task. The results showed that even though participants were not explicitly instructed to follow their avatar's movements, they adjusted their real arm positions to align more closely with the avatar's trajectory, deviating from their intended straight-line movement. Moreover, this tendency to follow the avatar's movement trajectory was diminished in the instantaneous distortion condition.

Furthermore, when the distortions were applied gradually, the sense of embodiment remained intact. However, when the distortions were introduced instantaneously, embodiment was negatively affected, although not entirely disrupted. This partial preservation of embodiment was likely due to the visuomotor synchronization between the real and the avatar's movements being maintained throughout the experiment. Later, Cohn *et al.* (2020a) extended these findings to the vertical axis, showing that participants adjusted their movement trajectories to follow the avatar even when the distortion was applied in the vertical direction, with deviations of up to 15 degrees.

The authors suggested that these motor adjustments, where participants' real hand movements increasingly aligned with the avatar's distorted trajectory, were driven by a need to resolve the visuo-proprioceptive conflict caused by a mismatch between the expected and visually perceived limb position. This process reflects an internal recalibration mechanism, in which the brain integrates conflicting sensory inputs and updates its body representation to maintain a coherent sense of embodiment.

However, it is important to note that in both studies (Cohn *et al.*, 2020a; Gonzalez-Franco *et al.*, 2020), a visual target was present in the virtual environment during each reaching trial. The distortion was implemented so that the avatar's hand always reached the visual target, regardless of the participant's actual hand movement. As a result, participants were not explicitly instructed to follow the avatar's trajectory. Nonetheless, the task design may have implicitly encouraged them to adjust their own movements to match the avatar's altered path in order to successfully reach the target. Therefore, the observed motor adjustments may reflect a strategy to optimize task performance rather than a spontaneous tendency to follow the avatar's distorted movements.

To further investigate the interaction between visuo-proprioceptive conflict and goal-directed reaching, Maselli *et al.* (2022) proposed a framework in which movement adaptations are driven by intentional control (goal-directed corrections to achieve a desired outcome by compensating for sensory discrepancies), conflict-resolution (motor adjustments made to reduce multisensory conflict), or a combination of both. In their study, participants performed a reaching task where a velocity-based distortion was applied to the virtual hand, making it move 1.3 times faster than the participant's real hand. The avatar followed the same trajectory but completed the movement in a shorter time, reaching the target before the real hand. This manipulation introduced a persistent spatial discrepancy between the actual and the avatar's movements, creating a visuo-proprioceptive conflict throughout the reach.

Their findings showed that participants were influenced by the distortion, with their real hand gradually shifting toward the trajectory of the faster-moving virtual hand. Because the reaching goal remained achievable despite the distortion, intentional control initially guided corrective adjustments. However, the persistent mismatch, due to the avatar consistently reaching the target ahead of the real hand, could not be fully resolved through intentional correction alone. As a result, conflict-resolution mechanisms were also engaged, gradually minimizing the ongoing sensory conflict and driving partial adaptation toward the distorted avatar trajectory.

Another study showed that introducing visuo-proprioceptive conflicts not only affects goal-directed reaching movements but can also significantly alter continuous movements. For example, Burin *et al.* (2019) investigated how body ownership modulates the interaction between observed and executed movements during a continuous drawing task. Participants were instructed to continuously draw straight vertical lines within a designated zone on a virtual tablet, while their embodied avatar's hand drew ellipses instead. As the task progressed, participants' drawings increasingly resembled the distorted avatar movements. This change was quantified using a movement similarity index (MSI), which measured the spatial overlap between the participant's drawn trajectory and the avatar's trajectory. The MSI significantly increased during the illusion condition compared to baseline, demonstrating that the mismatch between executed and observed movements prompted participants to draw more oval-shaped lines resembling the avatar's trajectories. The authors interpreted these findings as evidence that strong body ownership over the avatar alters how sensory prediction errors are processed. Specifically, when participants felt that the avatar's body was their own, they were more likely to interpret the visual mismatch not as an external error, but as a self-generated motor inaccuracy. As a result, instead of correcting their movement to match their intended action, participants adjusted their real movements to reduce the discrepancy between what they saw and what they expected to feel. This adaptation served to maintain a coherent sense of agency and bodily self, even in the presence of conflicting sensory input.

Furthermore, these effects were significantly stronger when the avatar's hand was perceived as the participant's own limb. In contrast, when the same task was performed from a 3PP, body ownership was diminished, and the extent of the adaptation, as reflected by lower MSI scores, was significantly reduced. These results further suggested that motor interferences occur because the prediction errors between expected and observed sensory feedback are weighted more heavily when the virtual hand is perceived as one's own. Moreover, when participants were asked about their performance in a post-experiment questionnaire, they reported continuing to draw straight lines, despite being explicitly aware of the experimental manipulation. This suggests that they remained unaware of their own adjusted performance, even though they consciously detected the visual distortion.

These unconscious motor adjustments were also observed in an elbow flexion task, where the avatar's movement amplitudes were altered without the participant's explicit knowledge. In this study, participants were instructed to bring their elbow to a 90° flexion while the avatar's arm flexion was modulated (Bourdin *et al.*, 2019). When the participant's real arm reached 90°, the avatar's arm was either reduced to 75° (-15°) or extended to 105° (+15°) relative to the real arm. The results showed a significant main effect of visual feedback on elbow flexion: when the avatar's arm was reduced to 75°, participants exhibited greater elbow flexion; when it was extended to 105°, they exhibited reduced flexion. Furthermore, these conditions induced high levels of ownership and agency towards the virtual arm. These findings indicated that altered visual feedback, when experienced with a strong sense of ownership, can significantly influence motor performance.

Motor adjustments have also been observed in response to changes in the perceived configuration or length of body features. Berger *et al.* (2022) explored this with the "Pinocchio illusion", where participants unknowingly adjusted their movements in response to a gradually elongating virtual limb. In this study, participants engaged in a task where they repeatedly tapped the virtual avatar's nose. With each tap, the virtual arm gradually elongated up to 50% of its original length, while the avatar's nose extended forward by up to 70 cm. This manipulation created a perceptual mismatch between the avatar's arm and the participant's real limb, prompting them to extend their real arm further along the anterior-posterior axis to compensate for the exaggerated virtual limb length. The extent of this adjustment was strongly influenced by the synchrony of feedback. When the virtual arm's elongation was synchronized with real tapping movements, the sense of ownership remained strong, leading to greater motor adjustments. However, the introduction of asynchronous feedback, achieved by delaying the visual elongation relative to the tapping, weakened the illusion of embodiment and reduced the extent to which arm movements adjusted to the virtual distortion.

The above-mentioned studies have indicated that motor adjustments can occur in response to distorted avatar movements; however, these effects have been examined primarily in the context of upper limb movements. In contrast, relatively little research has explored how lower limb motor behavior is influenced by such distortions. Moreover, the few studies that have investigated the effect on lower limb movements have focused mainly on temporal rather than spatial distortions in the avatar's movements.

Two studies by Boban and colleagues have (Boban *et al.*, 2023, 2024) demonstrated that visual feedback from a self-avatar can influence lower limb motor behavior, even in the absence of explicit instruction. In this first experiment (Boban *et al.*, 2023), participants performed rhythmic stepping while observing their avatar from a 1PP and simultaneously seeing it reflected in a virtual mirror. The avatar either moved in real time (synchronized) or followed a pre-recorded animation that was temporally delayed relative to the participant's actual movements. Despite the temporal mismatch, participants adjusted their stepping rhythm to align with the avatar's movements, reflecting a form of unintentional temporal synchronization.

The follow-up study by Boban *et al.* (2024) revealed that when participants were required to memorize and replicate a knee flexion sequence, their movements were strongly influenced by the avatar's movements. When the avatar's movements were deliberately manipulated to perform a different sequence (incongruent with the participant's intended actions), individuals were more likely to mirror the avatar's incorrect actions. This tendency was particularly evident during moments of uncertainty about the memorized sequence, highlighting how the visual feedback from the avatar can override participants' original motor intentions.

While the work of Boban and colleagues (Boban *et al.*, 2023, 2024) highlights that visual feedback from a self-avatar can influence lower limb motor behavior, the observed adjustment reflects a form of unintentional temporal synchronization, rather than a response to spatial discrepancies, which have been suggested to influence movement adaptation in the upper limb.

Taken together, these studies illustrate that embodied avatars can significantly influence motor performance. They demonstrate that when visuomotor congruency is preserved, healthy individuals tend to unconsciously adapt to altered motor feedback, minimizing discrepancies between their real and virtual bodies.

1.3.3 Virtual embodiment for motor rehabilitation

In healthy participants, the integration of multisensory cues leads the brain to attribute a virtual or fake limb as part of the user's body and incorporate an avatar in their body schema. The body schema refers to a dynamic, unconscious representation of the body's position, posture, and movement in space, constructed from continuous sensory input such as vision, proprioception, and touch (de Vignemont, 2010). Individuals suffering from neurological conditions such as stroke often disrupt body schema by impairing proprioception, motor coordination, and sensory integration, leading to difficulties in movement execution and limb awareness (Bolognini *et al.*, 2016; Mastria *et al.*, 2025).

Nevertheless, previous studies have demonstrated that stroke patients can still experience a sense of ownership over a rubber, despite these deficits. In fact, these illusory effects, as measured by both the proprioceptive drift and subjective reports of body ownership, are stronger in the affected hand compared to the same side in healthy controls (Llorens *et al.*, 2017; Burin *et al.*, 2015). These findings suggest that the deficits in proprioception and motor control, in the affected limb, lead to a more flexible sense of body ownership, which makes the brain more likely to be reliant on visual and tactile inputs to maintain a coherent body representation (Llorens *et al.*, 2017; Burin *et al.*, 2015). This increased dependence on alternative sensory inputs may cause the affected hand more susceptible to the illusion.

In contrast, the illusion does not occur in their unaffected hand (Burin *et al.*, 2015), even under synchronous stimulation, which has been shown to elicit a strong illusion in healthy participants (Botvinick & Cohen, 1998). The authors hypothesized that the unaffected hand undergoes increased use in daily activities, leading to a greater reliance on efferent motor commands and proprioceptive feedback. This reinforced sensorimotor integration strengthens body ownership for the unaffected limb, making it more resistant to the illusion.

The ability to induce body ownership in the affected side may have potential implications for stroke rehabilitation. For example, Aizu *et al.* (2023) found that illusory ownership over an actor's hand, induced through synchronous stimulation, led to increased range of motion (ROM) in the paretic index finger. In a non-immersive VR setup, participants viewed a video stream through an HMD. During the illusion induction phase, a paintbrush stroked the participant's finger while they watched a video of an actor's hand being stroked synchronously. Stroke patients were then instructed to imitate the cyclic finger movements of the actor's hand. The results showed a significant increase in the ROM of finger movement (approximately 6 degrees) in the synchronous condition. These findings suggest that ownership illusion can facilitate motor execution and may support the development of therapeutic interventions based on body ownership illusion.

In immersive VR, the full body illusion in stroke patients has been shown to elicit a sense of embodiment over full body avatars experienced from a 1PP, although the vividness of the illusion is often reduced compared to healthy controls (Borrego *et al.*, 2019). Virtual embodiment has also been explored in orthopedic rehabilitation, demonstrating improvements in motor recovery and ROM in musculoskeletal patients (Matamala-Gomez *et al.*, 2022; Álvarez De La Campa Crespo *et al.*, 2023).

For instance, Matamala-Gomez *et al.* (2022) examined the effects of virtual embodiment combined with exercises on patients recovering from distal radius fractures. Participants in the immersive VR condition observed their virtual arm from a 1PP while it executed instructed movements, reinforcing the sense of agency and embodiment. In contrast, the non-immersive VR group performed similar exercises but viewed the virtual arm on a laptop screen without experiencing the same level of embodiment. The immersive VR group exhibited significantly greater joint mobility and functional improvements, suggesting that the sense of ownership over the virtual arm enhances sensorimotor engagement and rehabilitation outcomes.

Similarly, Álvarez De La Campa Crespo *et al.* (2023) studied patients with movement-related shoulder pain who embodied an avatar from a 1PP, which replicated their movements in real-time. Initially, they observed a therapist avatar performing various shoulder movements, followed by their own avatar executing the same movements, although they did not physically perform them. Results revealed immediate improvements in subjective ratings of pain-free ROM of the shoulder, which the authors attributed to a prediction error. By observing an embodied avatar performing pain-free movements, patients may have expected pain that did not occur, leading them to perceive the movement as safe and allowing for greater ROM without triggering the usual pain response

The mere observation of an embodied avatar has also been shown to improve gait and balance deficits in stroke patients. In a study by Tambone *et al.* (2021), seated stroke patients observed an avatar walking, either from a 1PP, which induced an illusory sense of ownership and control, or from a 3PP. After 11 weeks of training, the 1PP group demonstrated significant improvements in gait speed, stride length, and balance performance, as measured by the Timed Up and Go test and the Berg Balance Scale. In contrast, the 3PP group did not exhibit the same level of improvement. The authors suggest that these benefits may stem from the reactivation of internal motor representations, which refers to the mental rehearsal or simulation of walking movements in the brain's motor areas, triggered when the avatar is perceived as part of the self, even in the absence of physical movement.

On the other hand, studies have explored how virtual embodiment combined with active movement, where patients control a self-avatar in real time, can be used to support functional recovery. For example, Fregna *et al.* (2022) has been shown that when actively engaging in a motor task while immersed in VR, it improves functional outcomes in a clinical population. They developed an immersive VR system for stroke rehabilitation in which patients could see and control a virtual hand from a 1PP while performing everyday upper-limb movements. The study reported high levels of embodiment, agency, and engagement. Patients' specific behavioral performances, such as task success rates, movement duration, and trajectory smoothness, were found to correlate with improvements in clinical motor recovery scores.

Furthermore, the movements of an embodied avatar can also be visually amplified, which has been shown to influence motor behaviour and promote the use of the affected limb in rehabilitation settings (Ballester *et al.*, 2015). In this study, stroke patients performed goal-directed reaching tasks in a virtual environment, where the movement of the paretic limb was subtly amplified, and exhibited increased spontaneous use of the affected limb in real-world settings. In this study, hemiparetic stroke patients performed goal-directed reaching tasks in a virtual environment while viewing their avatar from a first-person perspective on a computer screen. Their real arm movements were tracked in real time, and the avatar's movements were subtly enhanced in two ways: the extent of the movement was amplified to appear 1.4 times greater than the actual motion, and the direction was adjusted to more closely align with the target, effectively blending the real trajectory with an ideal one. This amplified feedback reinforced the idea that the action was successful, which in turn encouraged more spontaneous use of the paretic limb. Improvement was measured by tracking the frequency of voluntary use of the paretic arm during a free-choice reaching task, both during and after the intervention, with results showing a sustained increase even after the visual amplification was removed.

Together, these studies suggest the potential of virtual embodiment for motor rehabilitation. By embodying a first-person avatar, patients can observe their virtual limb executing movements, even those that may be limited or impossible in real life, which can lead them to perceive the avatar's movements as their own. This experience can reduce fear of movement (Álvarez De La Campa Crespo *et al.*, 2023), promote the active use of the affected limb (Ballester *et al.*, 2015) and potentially enhance recovery outcomes by supporting motor engagement and neuroplasticity recovery (Donegan & Sanchez-Vives, 2024).

1.4 The role of visual feedback distortion on human movement

1.4.1 Visual feedback distortion on gait

Visual feedback plays a crucial role in guiding and maintaining stable gait patterns. It provides essential information about the environment, enabling individuals to navigate obstacles, adjust foot placement, and maintain balance (Patla, 1997). However, manipulating the visual feedback can lead to significant changes in gait patterns with notable implications for gait adaptation. Studies using visual distortion paradigms have demonstrated that altering visual information can lead to subconscious modifications of gait.

For instance, Kim & Krebs (2012) showed that healthy participants unconsciously modulated their gait away from symmetry when presented with distorted step-length feedback. The right and left step length was measured during treadmill walking and were represented to the subjects as two vertical bars displayed on a computer screen. The bar height reached a maximum when the corresponding heel-strike occurred. Implicitly increasing one of the bar's heights led subjects to adapt to the distortion of visual feedback by unconsciously modulating their gait towards asymmetry. Even when adding a distraction task or even when being made aware of the distortion, the modulation of gait symmetry still occurred (Kim & Mugisha, 2014). Moreover, participants were not aware of their own gait adjustments when the distortions were applied implicitly or explicitly. The observed adjustments likely occurred because the distortion of the bars creates a prediction error between the actual step length of subjects and where the bar is displayed on the screen, as the latter is not where it is supposed to be. This led to an adjustment of the motor commands to modulate their actual step length accordingly.

Moreover, after these visual distortions are removed, gait asymmetries often persist temporarily. In both implicit and explicit distortion paradigm, it was observed that, following the removal of the visual distortion, participants' step lengths remained asymmetrical for several strides before gradually returning to baseline symmetry (Kim & Krebs, 2012; Kim & Mugisha, 2014).

A follow-up study by Maestas *et al.* (2018) further demonstrated that walking speed significantly modulates the effects of implicit visual feedback distortion on gait symmetry. In this study, participants walked at different treadmill speeds while receiving the same type of distorted step length feedback via visual bars. The results showed that gait adaptation, specifically, the degree of asymmetry induced by the visual distortion, was more pronounced at slower walking speeds.

At higher gait speeds, participants exhibited reduced sensitivity to the distortion, suggesting that slower gait allows more time for visual information to be processed.

Furthermore, Tobar *et al.* (2018) examined whether visual feedback could override physical perturbations. In their study, healthy participants walked on a treadmill with added mass attached to one leg, a manipulation that typically induces gait asymmetry. Despite this physical perturbation, when participants were exposed to a similar visual feedback distortion paradigm as previously used by Kim & Krebs (2012), they spontaneously adapted their gait and regained a more symmetrical step pattern. These findings suggest that visual feedback can dominate over proprioceptive inputs, driving gait adaptation even under physically asymmetrical conditions.

Expanding on this, Sato *et al.* (2022) explored how temporal distortion influences gait adaptation using a "virtual split-belt paradigm," where the visual feedback was distorted while the treadmill remained at fixed speeds. Participants walked on a treadmill while receiving continuous feedback about the position of their toes, represented by a blue dot, projected onto a large screen. They were tasked with landing their toe projection inside a target zone at each heel strike, which moved at the same speed as the treadmill. The feedback was then visually distorted by slowing down the target zone, creating the illusion that one leg was stepping further or shorter than the other. This induced asymmetry led participants to adapt their gait to match the slower-moving targets, leading to changes in both step length and step time. Post-adaptation aftereffects were also observed in this paradigm. Once the visual distortion was removed, participants exhibited a brief period of asymmetry in their step lengths and timings before readjusting to symmetric walking.

Within VEs the visual feedback can be delivered through a full-body avatar that represents the body in real-time. Liu *et al.* (2020) employed such real-time full-body feedback during gait and investigated the effect of real-time avatar-based feedback on gait symmetry in stroke survivors. Participants viewed an avatar replicating their own gait from different perspectives, including front, back, paretic-side, and non-paretic-side views. Unlike paradigms involving manipulated visual cues, the avatar's movements precisely represented the participant's gait in real-time. The results demonstrated that viewing the avatar from the paretic side led to significant improvements in spatial gait symmetry compared to other viewpoints. This suggests that real-time, self-representative visual feedback, particularly from a lateral perspective emphasizing the impaired limb, can facilitate motor adaptation and gait rehabilitation in individuals with asymmetric gait patterns.

A study conducted in our laboratory examined the impact of manipulating the stride length of a real-time self-avatar on gait parameters. In this experiment, healthy participants walked on a treadmill while viewing an avatar that mirrored their movements from a 1PP relative to the avatar (Willaert *et al.*, 2020). The avatar's stride length was gradually increased to assess whether the distortion would influence participants' own gait. While no statistically significant changes in stride length were observed on average, the results revealed a clear trend toward a gradual increase in stride length as the avatar's step length increased. Furthermore, a residual after-effect was detected once the manipulation was removed.

Janeh *et al.* (2019) implemented a fully immersive VE to examine how manipulated visual feedback affects gait symmetry in individuals with Parkinson's disease, who often exhibit asymmetrical step lengths. In the setup, virtual bars and virtual feet were displayed on a simulated walkway. The bars served as visual targets, representing the desired step length for each foot. To address gait asymmetry, the position of the virtual feet for the shorter leg was manipulated by shifting it backward relative to its actual position. The authors suggested that the visual-proprioceptive dissociation created a mismatch between the participant's proprioceptive feedback (their actual foot placement) and the visual feedback (the position of the virtual foot). This manipulation encouraged participants to adjust their step length, resulting in a more symmetrical gait pattern during the task.

1.4.2 The effect of altered visual feedback on reaching movements

Visual feedback plays a crucial role in guiding voluntary movements such as reaching, providing real-time information about the limb's position relative to a target. It provides real-time information about the position of the limb relative to a target. Research has shown that altering visual feedback can lead to systematic changes in motor behavior, as individuals adapt their movements to correct for perceived errors and maintain task performance.

A common method for this studying this adaptation is the visuomotor adaptation paradigm, where the visual representation of the hand's trajectory is systematically rotated relative to its actual movement path (Mazzoni & Krakauer, 2006; Taylor *et al.*, 2014; Henriques & Cressman, 2012). For instance, when participants reach toward a target but see their virtual hand veering left, they gradually compensate by adjusting their movements to the right. This compensatory adjustment realigns the visual hand with the target, reducing error and restoring accuracy. Such adaptation reflects the motor system's capacity to detect discrepancies between predicted and actual sensory outcomes and to update motor commands accordingly. Furthermore, when the distortion is removed, movements do not immediately return to their original trajectory. Instead, participants often exhibit aftereffects, continuing to compensate as if the distortion were still present.

Recent work has compared visuomotor adaptation in immersive VEs to conventional screen-based setups. In both conditions, participants used a digital pen and tablet to perform reaching movements toward visual targets, without seeing their actual hand. Visual feedback was provided solely through a red circular cursor displayed on a monitor in the conventional setup, and on a replicated virtual monitor within the immersive VE. A rotational distortion was applied to the cursor's trajectory in both environments, requiring participants to adjust their hand movements to compensate for the altered visual feedback. The study found that participants adapted at comparable rates and magnitudes in both conditions, demonstrating that immersive VR can effectively support error-based motor adaptation (Anglin *et al.*, 2017).

Building on this, Nardi *et al.* (2023) explored visuomotor adaptation during a real-world billiards task embedded in an immersive virtual environment. Participants were immersed in a VE while performing a billiards task using a physical cue stick and interacting with an actual cue ball on a real pool table. To induce a visuomotor distortion, the visual representation of the cue stick was rotated relative to its actual motion, requiring participants to adjust their real arm movements to compensate for the distortion. The authors found that participants were able to counteract the visual rotation and accurately direct the ball toward the target.

Research on reaching movements of the lower limb is relatively limited compared to the upper limb. In one study, participants performed a standing virtual ball-kicking task, where they used the position of their right foot to control a cursor representing the ball's location on a large screen positioned in front of them (Moriyama *et al.*, 2022, 2024). The trajectory of the virtual ball was manipulated by rotating it 15 degrees clockwise or counterclockwise relative to the actual ball direction. Participants adapted to these visuomotor distortions by adjusting their kicking trajectories in the opposite direction of the visual rotation, effectively realigning the ball's virtual trajectory with the target. This adaptation process was accompanied by anticipatory postural adjustments in the support leg to maintain dynamic stability and ensure accuracy during the goal-directed task (Moriyama *et al.*, 2024). These findings highlight the lower limb's capacity for visuomotor adaptation during complex tasks, despite the unique challenges associated with maintaining balance.

During the post-adaptation phase, when the visual distortion was removed, participants' lower limb movements showed curved trajectories, in contrast to the rotated trajectories commonly observed in the upper limb during similar adaptation tasks (Mazzoni & Krakauer, 2006). This distinction suggests that while lower limb biomechanics and motor control strategies differ, such as the added need for postural stability compared to the precision-driven control of the upper limbs, the underlying neural mechanisms governing error detection, sensory integration, and motor adaptation appear to be consistent across both limb types (Anglin *et al.*, 2017; Moriyama *et al.*, 2022, 2024).

1.5 Synthesis and research gaps

As discussed in this literature review chapter, manipulating visual feedback in immersive VR, particularly when presented through a virtual avatar, can alter users' perception of their own body and influence motor performance. A summary of the reviewed literature is provided in Table 1.1.

This effect has been demonstrated across a variety of experimental paradigms. For instance in foundational work on the rubber hand illusion (Botvinick & Cohen, 1998; Lanillos *et al.*, 2021; Asai, 2014), shows that synchronous visuotactile stimulation can induce a sense of ownership over artificial limbs, a phenomenon that has also been extended to the lower limbs, including the feet (Crea *et al.*, 2015; Lenggenhager *et al.*, 2015; Matsumoto *et al.*, 2020; Teaford *et al.*, 2021).

In goal-directed reaching tasks involving full-body avatars, spatial discrepancies between real and virtual limbs have been shown to prompt participants to follow the distorted avatar's movements, particularly when visual targets are present in the scene (Maselli *et al.*, 2022; Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020a; Burin *et al.*, 2019).

In the context of locomotion, a number of studies have shown that visual manipulations can significantly impact gait patterns. For example, providing real-time feedback through a third-person avatar has been shown to influence gait symmetry in stroke rehabilitation settings (Liu *et al.*, 2020). Similarly, altering the visual appearance of an embodied avatar, for instance, displaying the avatar as wearing high heels while the user walks barefoot, has been found to affect spatiotemporal parameters and joint kinematics (Oberdörfer *et al.*, 2024).

Additional studies using both implicit and explicit distortions of gait-related feedback have demonstrated changes in gait symmetry, often occurring without the participant's conscious awareness (Kim & Krebs, 2012; Kim & Mugisha, 2014; Tobar *et al.*, 2018; Maestas *et al.*, 2018). One study manipulating avatar stride length from a first-person perspective observed a non-significant trend toward increased stride length (Willaert *et al.*, 2020).

While these findings offer valuable insights into how manipulating the movements of virtual avatars can influence human behavior, several important research gaps remain, particularly regarding how gait symmetry, distortion detection thresholds, and the sense of embodiment are affected. Furthermore, in the context of goal-directed reaching movements, the extent to which visual targets influence participants' tendency to follow distorted avatar movements remains to be fully understood.

To date, the relationship between movement distortions and embodiment has been primarily studied in upper-limb tasks. These studies have identified detection thresholds, the level at which spatial distortions become consciously detectable, and explored how such distortions influence the sense of embodiment in immersive virtual environments (Porssut *et al.*, 2022a, 2019; Bovet *et al.*, 2018; Galvan Debarba *et al.*, 2018).

In contrast, relatively little is known about how distortion detection and embodiment interact in movements involving the lower limbs. Functional and sensory differences between the limbs (Hajnal *et al.*, 2007) suggest that the detection of such discrepancies may not generalize across modalities. For example, upper-limb movements involve voluntary motor control and visual guidance, while lower-limb movements are represented in a smaller area of the somatosensory cortex and are mostly involved in locomotion. These differences may influence both the detectability of avatar distortions and their impact on embodiment.

This gap is especially evident in the context of gait, which is a complex rhythmic motion driven by the nervous system's ability to coordinate movement with minimal conscious effort (Paul *et al.*, 2005; Malone & Bastian, 2010). While upper-limb studies have identified when distortions become consciously noticeable, it remains unknown whether and when such detection occurs during walking, particularly in response to spatial distortions that unilaterally alter the avatar's step length, and how this detection influences the sense of embodiment.

Another gap that emerges from the existing literature is the limited understanding of how embodiment can be re-established after it has been disrupted. Prior studies in upper-limb tasks have shown that embodiment can persist even when distortions become consciously noticeable, particularly when these distortions are introduced gradually (Porssut *et al.*, 2019). However, it remains unclear whether reducing a clearly detectable distortion, one that initially breaks the sense of embodiment, can restore embodiment if the distortion is gradually decreased to fall back below the detection threshold, without fully returning to perfect congruence and reintroducing the distortion incrementally.

Furthermore, the relationship between the detection of these distortions, the sense of embodiment and how these relate to effects on motor performance has not been investigated before. While upper-limb studies have shown that participants tend to follow the trajectory of a distorted avatar limb, even without explicit instruction, it remains unknown whether similar adaptations occur during gait.

Previous research has demonstrated that gait asymmetries can be induced through manipulated visual feedback, such as displaying altered step lengths on large screens (Kim & Krebs, 2012; Kim & Mugisha, 2014; Tobar *et al.*, 2018), or by changing the view of a third-person avatar reflecting the user's real-time movements (Liu *et al.*, 2020). Additionally, changes to the visual appearance of an embodied avatar viewed from a 1PP, such as wearing high heels, have been shown to influence gait parameters like stride length and joint kinematics, even when the avatar's movements remain fully congruent with the participant's own motion (Oberdörfer *et al.*, 2024). However, none of these studies directly manipulated the gait parameters of an embodied avatar's experienced from a 1PP. As such, it remains unknown whether unilateral step length distortions presented through a self-avatar can alter gait symmetry, and to what extent this adaptation is modulated by the user's sense of embodiment or their conscious detection of the step length distortion.

Finally, most existing research on distorted avatar movements has focused on upper-limb reaching tasks where visual targets were presented in the scene. These studies have shown that participants often adapt their movements to align with the avatar's trajectory (Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020a; Maselli *et al.*, 2022; Burin *et al.*, 2019). However, it remains unclear whether similar avatar-following behavior occurs during lower-limb goal-directed movements, which are typically more constrained due to postural demands and balance requirements. Moreover, no prior studies have examined whether increased balance demands, such as standing on one foot during lower-limb movements, modulate the extent to which participants follow distorted avatar trajectories.

Furthermore, these previous studies involved visible external targets, which may have encouraged alignment with the avatar primarily to accomplish the task. Participants may have reached for the target to comply with task demands, rather than out of a pure tendency to follow the distorted avatar movements. Whether participants still follow the avatar's movements in the absence of visual goals, and whether this behavior generalizes across different limbs, remains unknown.

Taken together, addressing these current gaps contributes to a better understanding of whether participants tend to follow the movements of a distorted avatar across different contexts, and whether this tendency is shaped by specific task constraints or the presence of visual targets.

Table 1.1 Summary of the relevant literature

Authors	**Distortion / Paradigm**	**Limb**	**Task**	**Visual Target**	**Key findings**
Stationary body ownership illusions					
Botvinick & Cohen (1998)	RHI	Hand	Observing rubber hand	No	Synchronous visuotactile stimulation induces proprioceptive drift and a sense of ownership over the rubber hand
Asai (2014)	RHI on movable board	Hand	Observing rubber hand	No	Physical drift towards the rubber hand
Lanillos *et al.* (2021)	Virtual Hand Illusion	Hand	Observing virtual hand	No	Participants generated corrective forces and micromovements toward the virtual hand, consistent with active inference mechanisms
Detection threshold and impact on SoE					

Authors	Distortion / Paradigm	Limb	Task	Visual Target	Key findings
Kokkinara *et al.* (2015)	Spatial and temporal distortion	Arm	Pointing	Yes	Spatial distortions of 11° and 22° were accepted without affecting ownership or agency. Temporal distortions (2× & 4× increased velocity) were consciously detected and reduced agency but not ownership
Bovet *et al.* (2018)	Spatial and temporal distortion	Arm	Goal-directed reaching	Yes	Detection thresholds for self-contact mismatches were lower with congruent self-contact, which also enhanced embodiment
Porssut *et al.* (2019)	Spatial distortion	Arm	Goal-directed reaching	Yes	Embodiment declined with increasing spatial distortion. 60% offset disrupted the sense of body ownership
Porssut *et al.* (2022a)	Spatial distortion	Arm	Goal-directed reaching	Yes	Reaching articular limits disrupted embodiment and reduced the threshold for detecting spatial distortions
Embodied avatar distortion					

Authors	**Distortion / Paradigm**	**Limb**	**Task**	**Visual Target**	**Key findings**
Bourdin *et al.* (2019)	Angular spatial distortion of elbow flexion ($15°$ and $-15°$)	Arm	Elbow flexion to 90°	Yes	Altered avatar flexion influenced real movement amplitude: participants increased flexion when the avatar flexed less, and decreased flexion when it flexed more, without conscious awareness and while maintaining embodiment
Burin *et al.* (2019)	Spatial trajectory distortion (avatar drew ellipses)	Hand	Drawing	Yes	Participants unconsciously adapted their drawings to match the distorted avatar trajectory by producing more elliptical movements. Adaptation was stronger under high ownership (1PP). Participants remained unaware of their motor adjustments despite consciously detecting the distortion

Authors	**Distortion / Paradigm**	**Limb**	**Task**	**Visual Target**	**Key findings**
Gonzalez-Franco *et al.* (2020)	Lateral spatial distortion	Arm	Goal-directed reaching	Yes	Participants gradually adapted their reaching to follow the avatar's lateral trajectory. Adaptation and embodiment were stronger with gradual distortion; both were reduced with instantaneous distortion
Cohn *et al.* (2020a)	Vertical spatial distortion up to 15°	Arm	Goal-directed reaching	Yes	Participants adjusted their reaching trajectories to follow the avatar, in the vertical axes
Maselli *et al.* (2022)	Velocity-based spatial distortion toward the target	Arm	Goal-directed reaching	Yes	Participants gradually adapted by moving their real hand trajectory toward the avatar's to reduce the visuo-proprioceptive conflict, engaging both intentional control and conflict-resolution mechanisms

Authors	Distortion / Paradigm	Limb	Task	Visual Target	Key findings
Berger *et al.* (2022)	Spatial distortion of the arm and nose elongation	Nose	Nose tapping	No	Gradual elongation of the avatar's arm and nose led participants to extend their real arm forward. Motor adaptation was stronger under synchronous feedback, which preserved ownership, and was reduced with asynchronous feedback
Boban *et al.* (2023)	Temporal distortion (delayed feedback)	Lower limb	Rhythmic stepping	No	Participants unintentionally synchronized their stepping rhythm with a temporally delayed avatar
Boban *et al.* (2024)	Temporal distortion (delayed feedback)	Lower limbs	Knee flexion sequence	Yes	Participants mirrored incorrect avatar movements, especially under uncertainty of the movement sequences
Distorted visual feedback on gait					
Kim & Krebs (2012)	Implicitly visual bar height distortion of step length	Gait	Treadmill walking	Yes	Implicitly increasing visual bar height for one foot led to unconscious gait asymmetry

Authors	Distortion / Paradigm	Limb	Task	Visual Target	Key findings
Kim & Mugisha (2014)	Explicitly visual bar height distortion of step length	Gait	Treadmill walking	Yes	Gait asymmetry occurred even with awareness of the distortion
Maestas *et al.* (2018)	Implicitly visual bar height distortion of step length at different speed	Gait	Treadmill walking	Yes	Gait asymmetry induced by visual distortion was more pronounced at slower gait speeds
Tobar *et al.* (2018)	Implicitly visual bar height distortion of step length under unilateral loading	Gait	Treadmill walking	Yes	Altered visual feedback overrode the effects of physical asymmetry, enabling participants to regain symmetric gait despite the perturbation
Liu *et al.* (2020)	Real-time full-body avatar presented on a screen (non modified)	Gait	Treadmill walking (stroke survivors)	Yes	Viewing the avatar from the paretic-side improved gait symmetry. Real-time, self-representative visual feedback from lateral perspectives enhanced motor adaptation
Embodied avatars during gait					

Authors	**Distortion / Paradigm**	**Limb**	**Task**	**Visual Target**	**Key findings**
Willaert *et al.* (2020)	Stride length avatar distortion	Gait	Treadmill walking	No	Gradually increasing the avatar's stride length led to a non-significant but consistent trend toward increased stride length. Aftereffects appeared after distortion removal
Oberdörfer *et al.* (2024)	Avatar wearing high heels	Gait	Barefoot treadmill walking	No	Embodying an avatar wearing high heels altered gait kinematics with shorter stride length, increased knee and hip flexion

CHAPTER 2

OBJECTIVES AND HYPOTHESES

2.1 Objectives

The main objective of this thesis is to better understand how spatial distortions applied to an embodied avatar influence participants' tendency to follow the avatar's movements, and to examine the interrelation between the distortions, motor adjustments, and the sense of embodiment.

To address this general objective, two experimental contexts were explored: (1) during gait with step length distortions, and (2) goal-directed upper- and lower-limb reaching without visual targets. The following specific objectives were defined:

1. To establish the threshold for detecting step length distortions below which users do not perceive the discrepancies between the gait of their avatar and their actual gait (O1).
2. To characterize the relationship between the detection threshold and participants' individual levels of subjective sense of embodiment (O2).
3. To investigate whether diminishing the amplitude of a detected step length distortion could restore the sense of embodiment (O3).
4. To assess whether altering the step length of an embodied avatar induces gait asymmetry in healthy participants, and to examine how the detection threshold of the distortion influences participants' gait adjustments and their relationship to changes in gait symmetry (O4).
5. To determine whether participants adjust their own upper and lower limb reaching movements to align with the avatar's trajectory when spatial offsets are introduced in the avatar's arm and leg movements (O5).
6. To assess whether increasing stability demands, by requiring participants to perform lower-limb reaching movements while balancing on one foot, would reduce their tendency to adapt to spatial distortions (O6).

2.2 Hypotheses

The main hypothesis of this thesis is that spatial distortions applied to an embodied avatar will lead healthy participants to align their real-world movements with the avatar's altered trajectory in these two contexts: (1) during gait with step length distortions, and (2) during goal-directed upper- and lower-limb reaching without visual targets.

This main hypothesis relies on the following specific hypotheses:

1. The point of detection of the step length distortion will lead to a break in embodiment during treadmill walking (H1).

2. During gait, when the step length distortion is reversed and gradually decreases, the SoE will remain consistent at a given distortion level, regardless of whether the distortion is increasing or decreasing (H2).
3. The gradual manipulation of the avatar's step length prompts participants to follow the distorted avatar's step length and adjust their own step length, thereby inducing asymmetrical gait patterns (H3).
4. The changes in gait symmetry are not affected by the conscious detection of the distortion and remain visible past the detection threshold (H4).
5. During goal-directed reaching movements of the upper and lower limbs, participants will adjust their actual limb movements to align more closely with the avatar's distorted trajectory (H5).
6. During lower-limb reaching movements, participants are expected to follow the avatar's distorted trajectory more closely when stability is promoted through external support, compared to when stability is challenged by balancing on one foot (H6).

CHAPTER 3

METHODS AND MATERIALS

3.1 Overview of the experiments and setup

This thesis includes two separate experimental protocols: The dataset for Articles 1 and 2 was collected from a single experiment involving 30 healthy participants, while a separate experiment with 24 healthy participants was conducted for Article 3. Both experiments were conducted in immersive virtual reality, developed in Unity 3D (Unity Technologies) in the LIO research laboratory located on the 7th floor of the CRCHUM, Montreal, QC, Canada (see figure 3.1).

Participants were represented by anthropometrically personalized self-avatars, created using MakeHuman (MakeHuman Community) and integrated into the virtual environment. Real-time avatar animation was achieved through a full-body motion capture system using Vicon T20-S infrared cameras (200 Hz), with rigid body clusters placed on major anatomical segments (3.2 A). The motion data were streamed in real time via Vicon Tracker and retargeted to the avatar skeleton using Vicon Pegasus (3.2 B). An integrated inverse kinematics (IK) solver aligned the avatar's joints with the participant's tracked movements, allowing for synchronized, first-person embodiment within the virtual environment (3.2 C). Detailed descriptions of the experimental procedures and protocol-specific implementations can be found in Articles 1 to 3 (Chapters 4 to 6).

Figure 3.1 Experimental setup and materials. (A) The LIO research laboratory. (B) The VE, a replica of the LIO laboratory with real-life dimensions of the treadmill and safety bars. (C) The HTC Vive Pro Eye HMD used in the first experiment and fitted with reflective markers for tracking by the Vicon motion capture system. (D) Meta Quest 3, used in the second experiment, is equipped with reflective markers to create a rigid body.

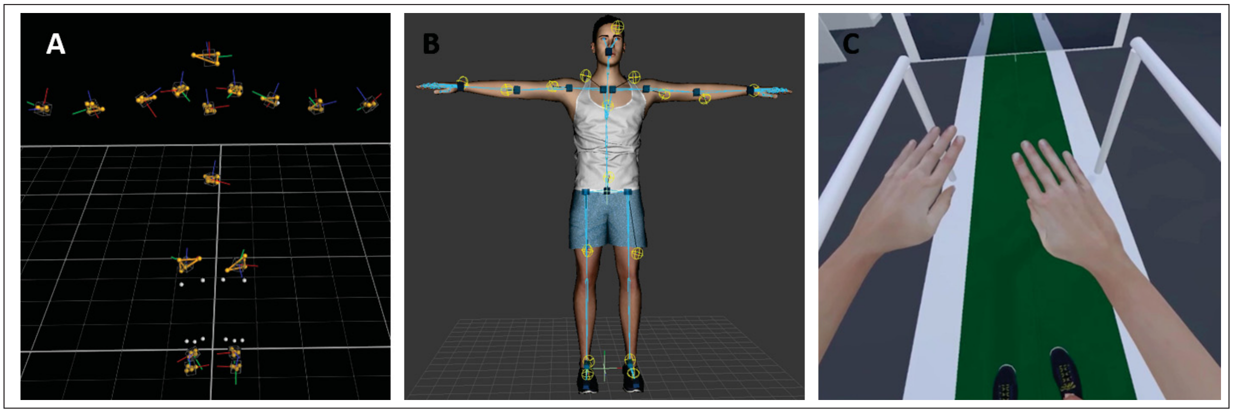

Figure 3.2 (A) Rigid body clusters tracked in real time using Vicon Tracker. (B) Retargeting of participant limb position and orientations onto the avatar in Vicon Pegasus. (C) A participant experiencing their virtual avatar from a first-person perspective in the virtual environment.

3.2 Step length distortion model

An algorithm was developed to dynamically and unilaterally manipulate the avatar's step length in real time, while preserving visuomotor congruence between the user and the avatar. The pseudocode illustrating the algorithm's logic is provided in Algorithm 3.1.

The step length distortion algorithm was used to address the research objectives of Articles 1 and 2. A detailed description of the algorithm's logic is documented in the respective publications:

- Article 1 (Chapter 4): The algorithm was employed to determine the threshold at which participants could perceive the discrepancy between the distorted step length of the avatar and their actual step length.
- Article 2 (Chapter 5): The algorithm was utilized to analyze the impact of distorted step length on gait symmetry, focusing on how participants adapted to these changes and whether the induced asymmetry affected their gait.

3.2.1 Step length distortion validation

To ensure the accuracy of the step length manipulation algorithm, a validation was carried out to test its ability to apply precise spatial distortions during gait. The validation aimed to confirm two key points: (1) that the avatar's step length increased in precise 1% increments relative to the participant's baseline step length, and (2) that the algorithm accurately computed the avatar's step length by comparing it with measurements obtained from the Vicon motion capture system.

The validation was conducted with three participants. During a single walking sequence, the step length was progressively increased by 1% every 10 strides, up to a total of 20 distortion levels per participant. To prevent any influence on natural gait, participants did not see the modulated avatar during the task. Instead, they saw their avatar replicate their actual movements in real time.

A comparison between the avatar's computed step length and Vicon-based measurements is provided in Appendix I-1). The results confirm that the algorithm successfully applied the intended 1% step length increases and that the avatar's computed step lengths closely matched the reference measurements. The mean standard deviation (SD) between the two methods was 0.004 m, indicating minimal differences in step length. This agreement demonstrates that the algorithm was capable of lengthening the avatar's step length as intended.

Algorithm 3.1 Step Length Distortion Model. AP = antero-posterior axis, ML = medio-lateral axis, Vertical = vertical axis.Foot and hip positions are represented in 3D coordinates consistent with Unity's world axes: AP corresponds to the forward–backward (z) direction, ML to left–right (x), and Vertical to up–down (y). The distortion is applied only along the AP axis, modifying the antero-posterior component of the IK target.

Input:
Current foot position (3D): `footPos`
Current hip position (3D): `hipPos`
Distortion magnitude as a percentage of the baseline: `distortionMagnitude`
Maximum posterior position of the foot: `maxPostDistance`
Maximum anterior position of the foot: `maxAntDistance`
MaxAnterior-to-MaxPosterior distance ratio: `apRatio`

Output:
Updated IK target position: `IKTarget.position`

```
Update // called every frame in Unity
startValue ← 0
endValue ← distortionMagnitude
if Foot moves forward along the AP axis then
    ratio ← (footPosAP - hipPosAP) / maxAntDistance
    spatialOffset ← linearInterpolation(startValue,endValue,ratio)
end if
else if Foot reached max position and starts moving backwards along the AP then
    ratio ← (footPosAP - hipPosAP) / maxPostDistance
    apRatio ← maxAntDistance / maxPostDistance
    spatialOffset ← linearInterpolation(startValue, apRatio x
     endValue,ratio)
end if
// Set IK Target Position
IKTarget.position ← (footPosML, footPosVertical, footPosAP +
 spatialOffset)
```

3.3 Reaching distortion model

To investigate the impact of spatial distortion on motor performance during upper and lower limb reaching movements, a reaching distortion algorithm was developed and implemented in the study presented in Article 3 (Chapter 6). The algorithm dynamically manipulated the position of the avatar's arm or leg to introduce a gradual spatial offset relative to the participant's actual limb movements, while maintaining visuomotor synchronization.

The algorithm's logic is described in detail in Article 3. The pseudocode illustrating the algorithm's logic is provided in Algorithm 3.2.

3.3.1 Reaching distortion validation

To ensure the accuracy of the reaching distortion algorithm, a validation procedure was conducted during the upper limb reaching task to confirm its ability to apply angular shifts in the avatar's endpoint trajectory. The validation assessed three key aspects: (1) whether the Endpoint displacement increased by approximately 1-degree lateral increments relative to the participant's current shoulder or projected hip position on each reach, (2) whether the cumulative displacement over 20 reaches approximately the intended total of 20 degrees, and (3) whether the avatar's limb consistently advanced laterally along the predefined path, regardless of the user's reaching behavior.

The validation involved two illustrative movement strategies performed in the upper limb task: one in which a user consistently counteracted the distortion by reaching medially in the opposite direction of the avatar, and another in which the user initially counteracted and then followed the distortion by reaching laterally in the same direction as the avatar. Across 20 successive reaches, a 1-degree angular shift was applied to the Endpoint along the circumference of the predefined circular path centered on the shoulder joint. Because each angular update was based on the participant's current shoulder position, rather than a fixed origin, slight deviations in angular displacement were expected due to natural movement variability during the task.

The avatar's limb trajectory followed the intended lateral progression, confirming that the algorithm was capable of applying the lateral distortion regardless of the user's reaching behavior, while dynamically accounting for natural changes in posture. A summary of the updated Endpoint and user responses is provided in Appendix I-2.

Algorithm 3.2 Avatar Reaching Distortion Algorithm (AP = antero-posterior axis, ML = medio-lateral axis, Vertical = vertical axis).

Input:

Current limb position: (3D): `limbPosition`
Current joint position (3D): `jointPosition`
Current limb rotation: `limbRotation`
start and end point positions: `startPointPosition, EndPointPosition`
Previous angular drift: `previousAngle`
Angular drift per reach: `driftAnglePerReach`

Output:

Updated IK target position: `IKTarget.position`

```
Update //  called every frame in Unity
// Calculate Direction
targetDirection ← limbPosition - startPointPosition
// Calculate Horizontal Distance
horizontalDistance ← distance(limbPosition, startPointPosition)
// Update IK Target Position
scaledDirection ← targetDirection x horizontalDistance
newPosition ← startPointPosition + scaledDirection
IKHandTarget.Position ← newPosition
KHandTarget.Rotation ← limbRotation

On Target Hit
if StartPoint or Endpoint is Hit then
    // Determine Target Parameters
    target ← EndPointPosition or StartPointPosition // Depending on
     which target (start or end) was hit
    targetPosition ← EndPointPosition or StartPointPosition
     // Depending on which target (start or end) was hit
    // Calculate Target Radius
    radius ← distance(jointPosition, targetPosition)
    // Calculate New Angle
    NewAngle ← previousAngle + driftAnglePerReach
    // Update Target Position
    newTargetML ← jointPositionML + radius x cos(newAngle)
    newTargetAP ← jointPositionAP + radius x sin(newAngle)
    targetPosition ← (newTargetML, targetPositionVertical,
     newTargetAP)
    // Update Previous Angle
    previousAngle ← newAngle
end if
```

CHAPTER 4

DETECTION THRESHOLD OF DISTORTED SELF-AVATAR STEP LENGTH DURING GAIT AND THE EFFECTS ON THE SENSE OF EMBODIMENT

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4.1 Context and contribution

Chapter 4 presents the first experimental study of this thesis and addresses Objectives 1 to 3 by investigating how healthy participants perceive step length distortions applied to an embodied avatar during gait, and how these distortions affect the sense of embodiment.

This study makes three key contributions to the thesis. First, it introduces the concept of a detection threshold for spatial distortions during gait using a self-avatar with asymmetric step lengths. Second, it explores the relationship between distortion magnitude, the detection threshold and the sense of embodiment. Third, by employing a descending approach, the study investigates whether reducing a large, clearly detectable distortion can re-establish the sense of embodiment, rather than requiring a complete return to perfect alignment between the user and the avatar, as commonly done in previous established methods to induce the sense of embodiment.

The contributions of this paper support a deeper understanding of how spatial distortions applied to an embodied avatar are perceived and tolerated during gait in immersive virtual environments, and offer new insights into how the sense of embodiment is affected by the step length distortion and how it can be restored under such conditions.

4.2 Abstract

In immersive VR, a self-avatar that replicates the user's movements and is viewed from a first-person perspective can substitute for the real body. If the avatar's movements are sufficiently synchronized with the user's actual movements, the user can experience a sense of embodiment over the avatar. Recent studies have shown that discrepancies between the movements of the avatar and those of the user can be well tolerated while maintaining high levels of embodiment. The point at which a distortion is perceived (detection threshold) and its impact on the level of embodiment has not been studied in lower limb tasks such as gait. This study aimed to identify a detection threshold of gait asymmetry by unilaterally manipulating the step length of a self-avatar, and the effect of this detection on perceived embodiment. A real-time step length distortion model was developed, and a detection threshold between actual and avatar's gait movement was assessed on thirty healthy participants. The step length was manipulated to introduce gait asymmetry (ascending condition) or start from a large asymmetry that was gradually decreased (descending). The results showed that, on average, the avatar's step length could be increased by up to 12% before the participants detected the distortion. Furthermore, in the descending condition, they detected increases that were above 9%. The point of detection had no effect on the sense of embodiment as participants still reported being embodied in their avatars, even when they consciously detected the step length distortion. The sense of embodiment was closely correlated with the level of distortion; as distortion increased, embodiment decreased, and vice versa. For a given distortion level, embodiment was similar whether in the ascending or descending condition. This suggests that embodiment can be achieved even when the avatar's spatial alignment initially differs from the participants', provided that alignment is gradually restored. These results provide valuable insights into participants' ability to tolerate movement discrepancies in embodied avatar experiences during gait in virtual environments, with potential applications in motor training and gait rehabilitation.

4.3 Introduction

In immersive virtual reality (VR), a self-avatar that mimics the user's movements and is viewed from a first-person perspective (1 PP) can act as a substitute for the user's real body, which is not visible from within the virtual environment (VE). When the avatar's movements are accurately synchronized with the user's own movements, it can create a sense of embodiment (SoE) over the avatar (Spanlang *et al.*, 2014). This SoE is commonly recognized to consist of three primary components: body ownership, agency, and self-location (Kilteni & Slater, 2012). Body ownership refers to the attribution of the virtual body to oneself. The sense of agency pertains to the feeling of having global motor control, where one can initiate and control the movements of the virtual body. Self-location refers to the perception of being located within the virtual body.

Extensive research has demonstrated that embodiment in VR is robust and can produce a particularly convincing illusion (Slater *et al.*, 2008; Banakou *et al.*, 2013; Kokkinara *et al.*, 2016). The congruence between the user's movements and their avatar's movements is considered a critical factor in generating and sustaining the SoE (Maselli *et al.*, 2015). Congruent visuotactile stimulations (where users simultaneously experience tactile sensations and observe their avatar's corresponding body parts being touched) can also induce embodiment, but their contribution to the overall illusion is lesser in comparison to visuomotor stimulations (Kokkinara & Slater, 2014). Conversely, visuomotor and visuotactile stimuli that are incongruent, at any point during the experience, have both been shown to equally lead to a loss of the illusion, in what Kokkinara & Slater (2014) called a break in the SoE.

Nevertheless, it has been shown that self-avatar movements that are spatially distorted with respect to those performed by the user can still be accepted and not break the SoE (Bourdin *et al.*, 2019; Burin *et al.*, 2019; Porssut *et al.*, 2019; Cohn *et al.*, 2020a). For instance, Kokkinara et al., 2015 found that participants accepted a spatial distortion in the form of 11° and 22° angular offsets, applied to the shoulder, during a reaching movement with the arm fully extended. Notably, this distortion did not impact body ownership or agency, as perceived by the participants. However, when spatiotemporal distortions were applied (increased velocities of 2x and 4x), they were consciously detected, which diminished the reported level of agency but not the level of ownership.

Porssut *et al.* (2019) conducted a study exploring various levels of spatial distortions between real and avatar hand positions while participants were instructed to follow a target with their hand. They observed that ownership and agency scores decreased as the magnitude of distortion increased. Despite the decrease in the level of embodiment, participants still reported feeling a SoE in their avatars, even when consciously aware of the spatial mismatch. They employed an approach that differed from that of Kokkinara & Slater (2014) to compute embodiment scores which were based on the frequency of reported breaks in the SoE. They identified a critical threshold of 60%, beyond which a significant distortion ultimately broke the SoE. Notably, this threshold can be extended if the distortion is intentionally designed to assist in achieving a particularly challenging task (Galvan Debarba *et al.*, 2018; Porssut *et al.*, 2019; Delahaye *et al.*, 2023). Conversely, factors such as incongruent haptic feedback in the form of a spatial mismatch during self-contact significantly decreases body ownership and agency (Bovet *et al.*, 2018). Additionally, a discrepancy between internal proprioceptive feedback and the feedback that would be expected given the avatar's position (such as the realization of a mismatch between one's own arm reaching full extension before the avatar's arm does) can also disrupt embodiment (Porssut *et al.*, 2022a).

In addition, the manner in which the distortion is applied has an impact on its level of acceptance. Instantaneous distortions are generally poorly tolerated and diminish embodiment due to the abrupt introduction of sensory conflicts (Porssut *et al.*, 2019; Cohn *et al.*, 2020a; Gonzalez-Franco *et al.*, 2020). Conversely, gradually applied distortions can increase the detection threshold and enhance acceptance (Porssut *et al.*, 2019). Instantaneous distortions cause a significant change in the avatar's movements, negatively affecting embodiment, yet they do not result in a complete break in embodiment as long as visuomotor synchronization between the avatar and real movements is maintained. In fact, when these abrupt distortions are suddenly removed, thereby restoring visuomotor congruency, embodiment begins to rebuild even in the case of semantic violations (Padrao *et al.*, 2016; Cohn *et al.*, 2020a; Gonzalez-Franco *et al.*, 2020). It remains unclear whether, once the SoE has been broken, it can also be regained by gradually decreasing the magnitude of distortion to bring it back below the threshold rather than reverting to perfect congruence (no distortion) and having to gradually re-increase the distortion. Previous studies have identified a detection threshold through adaptive staircase methods for spatiotemporal distortions during hand-reaching movements, gradually reducing the magnitude until this threshold was reached (Bovet *et al.*, 2018; Galvan Debarba *et al.*, 2018). Although these studies demonstrated that a large distortion exceeding the detection threshold can go unnoticed again when its intensity is decreased, they did not evaluate the impact of the adaptive staircase method on the SoE.

When users perceive the movements of their self-avatar as being their own and are not aware of applied distortions, this allows experimenters or clinicians to act upon the perception-action loop by modifying the visual feedback observed in response to motor commands. This could be exploited by intentionally amplifying errors made by individuals during their motor tasks or exercises. By emphasizing and accentuating errors, individuals become more aware of their movement discrepancies and are more likely to engage in cognitive processing to correct those errors (Reisman *et al.*, 2013; Janeh *et al.*, 2019). Conversely, the self-avatar can also be programmed to perform a distorted movement that is closer to the intended movement than the one that a patient produces. Indeed, when users are embodied in their self-avatars onto which spatial distortions are applied, they tend to follow their avatar's movements by unconsciously adjusting their movements to match those of their avatar in order to reduce the discrepancy between what is seen (visual information) and what is felt (proprioceptive feedback) (Bourdin *et al.*, 2019; Burin *et al.*, 2019; Cohn *et al.*, 2020a; Gonzalez-Franco *et al.*, 2020). This phenomenon, recently coined by Gonzalez-Franco *et al.* (2020), as the "self-avatar follower effect," has possible implications for motor rehabilitation.

One potential application of applying such manipulations to the movements of an embodied self-avatar is for the rehabilitation of patients who suffer from gait asymmetries, which are commonly observed in a neurological population (Patterson *et al.*, 2008). Spatiotemporal distortions could be applied to alter the asymmetry of the avatar's gait in order to drive unconscious corrections (Willaert *et al.*, 2020). If embodiment is maintained, patients may perceive the distorted avatar movements as their own, which could implicitly affect their movements to alter their gait and potentially help reduce gait asymmetries. For such applications of embodied self-avatars, it is important to have a good understanding of the extent to which an avatar's movements can be distorted without conscious detection by its user and without causing a break in embodiment.

The relationship between movement distortions and embodiment has primarily been explored in the context of upper limb movements, such as reaching tasks. Research involving lower limb movements is relatively limited, though functional demands and sensory properties differ between the upper and lower limbs (Hajnal *et al.*, 2007). For instance, upper limb movements are involved in executing voluntary movements and exhibit fine motor control, while the lower limbs have a smaller representation in the somatosensory cortex and are mostly involved in locomotion. The detection of discrepancies between apparent (avatar) and actual performed movements (participants) may therefore differ between the upper and lower limbs. This is particularly true in the case of gait, which is a complex rhythmic motion driven by the nervous system's ability to coordinate movement with minimal conscious effort (Paul *et al.*, 2005; Malone & Bastian, 2010) and is usually less visually guided, unlike reaching movements that require more deliberate motor planning and execution (Miall & Wolpert, 1996).

This study aims to better understand the relationship between the amplitude of spatial distortions applied to a self-avatar's gait, their conscious detection, and the ensuing SoE. This understanding is necessary for applications in gait rehabilitation seeking to address asymmetry by manipulating one limb of the self-avatar. We employed a virtual self-avatar whose step length was unilaterally increased, thereby producing an asymmetrical gait pattern. The step length distortions were gradually applied and the direction of the distortion was systematically altered over time. The first objective was to establish the threshold for detecting distortions (specifically, step length asymmetry) below which users do not perceive the disparities between the gait of their avatar and their actual gait. The second objective sought to characterize the relation between this detection threshold and users' individual levels of subjective SoE. Lastly, a tertiary objective was to investigate whether diminishing the amplitude of a detected step length distortion could restore the sense of embodiment.

We applied step length distortion to both the dominant and non-dominant legs, as prior research has indicated that limb differences exist during able-bodied walking, which may be attributed to limb dominance (Sadeghi *et al.*, 2000). Moreover, proprioceptive acuity has been found to vary between the dominant and non-dominant lower limbs (Han *et al.*, 2013). Furthermore, there's evidence suggesting that proprioceptive drift, where one's sense of the location of their body parts shifts towards an external stimulus, is less pronounced in the dominant hand compared to the non-dominant hand. This is likely because proprioceptive information associated with the dominant limb is more stable, leading to a decreased drift (Dempsey-Jones & Kritikos, 2019) . These findings suggest that limb dominance can impact both motor control and perception, implying that the dominant and non-dominant lower limbs may respond differently to the step length distortion, which may impact the detection threshold. Therefore, this study also aims to explore how limb dominance influences the ability to detect spatial distortions and its impact on the sense of embodiment.

Our initial hypotheses posited that embodied users can detect unilateral step length distortions of the self-avatar (H1). Given prior findings suggesting that users can eventually detect significant avatar distortion during upper movements (Galvan Debarba *et al.*, 2018; Porssut *et al.*, 2019, 2022a), we anticipate that participants will similarly detect the distortions during gait, as these gradually increasing step length distortions eventually present an asymmetry that deviates from their typical symmetrical gait. Moreover, we hypothesize that the detection of these distortions will lead to a disruption in the SoE (H2). As the distortions gradually deviate from participants' natural gait patterns, the conscious awareness that the avatar no longer replicates their body movements is likely to have a negative impact on their SoE. Lastly, when the step length distortion is reversed and gradually decreases, we hypothesize that the SoE will remain consistent at a given distortion level, regardless of whether the distortion is increasing or decreasing (H3). Since the congruence between the user's movements and the avatar's movements enhances the SoE (Kilteni & Slater, 2012), it is plausible that the SoE can be restored as the incongruences diminish. In other words, we expect that the decreasing distortion will positively impact the SoE, indicating that the level of SoE is influenced by the magnitude of the distortion rather than its direction.

The contributions of this paper are threefold: (i) Defining a detection threshold for gait distortions in a self-avatar with unilaterally increased step length during healthy gait; (ii) exploring the impact of the detection threshold on SoE and its interaction with limb dominance; (iii) examining the restoration of the SoE through reduction of large, detected distortions.

4.4 Methodology

4.4.1 Participants

Thirty-five healthy participants volunteered to take part in this study. Inclusion criteria were to have no pathological, medical or lower limb conditions that could affect gait. Ethical approval was obtained (CE15.104) through the Research Ethics Boards of Centre hospitalier de l'Université de Montreal (CHUM) and of Ecole de technologie supérieure (ETS). All participants signed written consent and completed a demographic questionnaire before the start of the experiment. Participants were compensated $40 CAD for their participation.

4.4.2 Virtual environment and avatar

The VE was developed with Unity 3D game engine version 2019.3.13f1 (Unity 3D) and was a replica of our research lab with a large virtual mirror placed 1.0 m in front of the virtual treadmill. The dimensions of the virtual treadmill and the safety railings correspond with that of the real world to ensure safe walking in the VE (Figure 4.1A). The VE was visualized through a head-mounted display (HMD), HTC VIVE Pro Eye (1,440 × 1,600 pixels per eye, 90 Hz refresh rate, 110° field of view) with a first-person perspective (1 PP) relative to the avatar (Figure 1B). The HMD was connected to a desktop PC with an 8 GB Nvidia GeForce RTX 3070 graphic card, 64 GB of memory and 1 TB SSD. A female and male avatar were designed in MakeHuman 1.20 (MakeHuman) and were individually scaled to match the height and weight of each participant, ensuring an anthropometrically personalized representation. Further customization was performed based on the participants' gender and skin color to increase avatar resemblance. The female avatar wore a white T-shirt, and the male avatar wore a grey T-shirt. Both avatars wore blue shorts and black sneakers (Figures 4.1A,B). This standardized clothing choice aimed to maintain consistency across participants and minimize potential biases introduced by varying clothing.

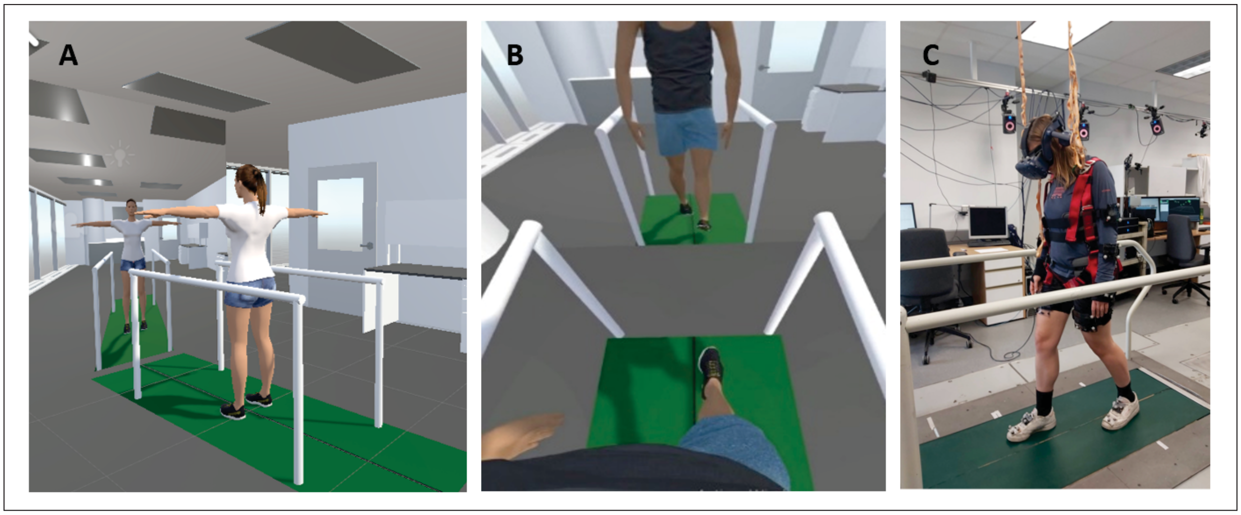

Figure 4.1 Experimental setup. (A) The VE, female avatar and virtual treadmill and virtual mirror, (B) A male participant's avatar walking in the VE in front of the virtual mirror, viewed in 1 PP, (C) A participant wearing the mocap clusters, the HMD and a safety harness.

4.4.3 Equipment and software

The experiment was performed on a split-belt treadmill (Advanced Mechanical Technology Inc., 187 Waterdown, MA, United States), which has two belts that can be controlled separately, allowing for different speeds or directions of movement. In our experiment, the speeds of both belts were identical throughout. During the experiment, participants were fitted with a safety harness to support their weight in the event of a fall due to loss of balance while walking on the treadmill. They were further equipped with 14 rigid body marker clusters placed with Velcro straps on specific body parts (toes, feet, upper legs, pelvis, hands, elbows, upper arms, and between the shoulders) (4.1C). The marker clusters were tracked in real-time by 12 Vicon T20-S cameras (Vicon Motion Systems Ltd., Oxford, United Kingdom) running the Vicon Tracker 3.6 software. Vicon Pegasus Advanced 1.2.2 (Vicon Motion Systems Ltd., Oxford, United Kingdom) retargeted the limb positions and orientations onto the virtual avatar and displayed them in the VE in real-time. Vicon software (Tracker and Pegasus) was run on a separate desktop PC equipped with a 4 GB Nvidia Quadro M2000 graphic card and 32 GB of memory, and a 500 GB SSD.

4.4.4 Real-time step length distortion model

An algorithm was developed to dynamically alter one step length of the avatar in real-time, inducing gait asymmetry. The avatar's step length is modified by gradually introducing a spatial offset between the avatar's ankle and the user's actual ankle position along the AP axis of the tibia (Figure 4.2). The spatial offset linearly increases starting at mid-swing, identified as the moment the ankle is directly under the hip joint, during the forward swing of the gait cycle (Figure 4.2A). The spatial offset gradually causes the avatar's ankle to advance along the AP axis of the tibia until heel strike. Conversely, the offset starts decreasing at heel strike (Figure 4.2B), crossing into a negative offset at midstance that increases until heel off (Figure 4.2C). At this point, the negative offset is gradually decreased, reaching a null offset at mid-swing. The ratio of the positive to negative offset that is applied is equal to the ratio between the most anterior and most posterior positions of the ankle, relative to the hip joint, for each participant.

The resulting kinematics of the lower limb of the avatar are computed using an IK with FinalIK (RootMotion). To preserve the visuotactile synchronization, which has been shown to maintain the SoE (Kokkinara *et al.*, 2015), the avatar's (distorted) heel strike is always synchronized with the heel strike of the user.

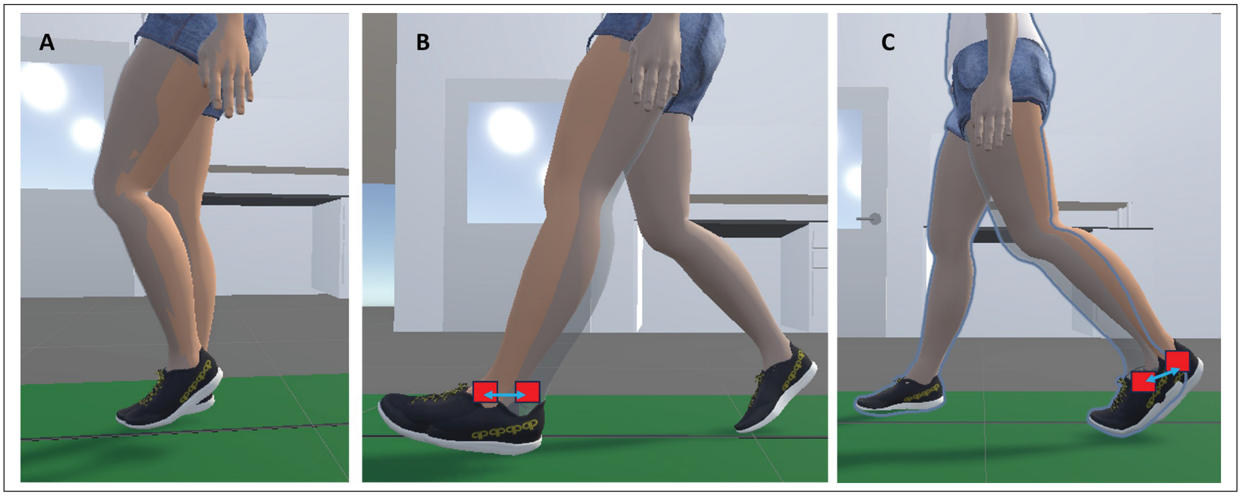

Figure 4.2 Left step length distortion (lateral view). The translucent avatar represents the participant's actual leg position, and the opaque avatar illustrates the distorted position of the left lower leg. The blue arrow represents the offset value. Participants were not able to see the translucent avatar or red cubes, and saw their avatars from a 1 PP. (A) The avatar's left limb reaches mid-swing. The AP offset of the ankle is null and starts increasing linearly along the AP axis of the tibia. (B) The avatar's left heel contacts the ground (heel-strike). Maximum positive offset of the ankle is reached, and it starts decreasing. (C) The avatar's left heel loses contact with the ground (heel off). Maximum negative offset of the ankle is reached and it starts decreasing, reaching a null offset at mid-swing (A).

4.4.5 Experimental setup and protocol

Participants were invited to perform the experiment in one single session, which lasted 3h30. A schematic overview of the protocol can be found in (Figure 4.3A). First, dominance was determined by asking participants to kick a foam ball towards the wall. The foot used to kick was deemed the dominant one.

4.4.5.1 Calibration and baseline

The experiment started with a 5-min period of treadmill walking without wearing the HMD or viewing the VE. This was done to familiarize participants with walking on the treadmill, to ensure that the marker clusters had been placed correctly and were not slipping, and to determine their self-selected gait speed. The latter was obtained by slowly increasing the speed of the treadmill until participants indicated that they felt comfortable and were walking at a pace that they considered natural and preferred. Participants were then fitted with the HMD and the avatar was calibrated to collocate with the position of the participants. During this calibration phase, participants were asked to look straight ahead with their feet pointing straight forward and their arm resting along their body. The avatar was not visible, to prevent the participants from observing visual artifacts. Once the calibration phase was completed, participants were asked to move their lower and upper limbs for 1 minute while observing their movements being performed by their avatar, alternating between looking directly down at their virtual body and looking ahead to view their virtual body in the mirror. This was done to induce the feeling of embodiment. This active visuomotor control has been shown to induce the experience of body ownership over a virtual avatar (Kokkinara & Slater, 2014). A 5-min period of walking while wearing the HMD was then imposed in order to familiarize participants with walking in the VE. For this period and for the entire experiment, participants were instructed to alternate between looking in the mirror and looking down at their virtual body. This was done to ensure that participants saw their avatar's lower limbs, whose movements were manipulated. They were further instructed not to hold the safety railings while walking and to inform the experimenter immediately if any dizziness, nausea, or any discomfort occurred so that the experiment could be stopped. During the last 2 minutes of this baseline period, the participant's average step length was calculated.

4.4.5.2 Experimental phase

The experimental phase of this study was divided into four conditions (Figure 3) during which the detection threshold between the participant's gait and their avatar's gait was assessed. The four conditions were randomized across participants and lasted 15 min each. The conditions consisted of two ascending and two descending conditions. In ascending conditions, the step length of the avatar was gradually increased from baseline (no distortion) to a maximum of 30% increase of their baseline step length, in 1% increments at every 10 strides. Conversely, in the descending conditions, the step length of the avatar was initially set to 30% of the baseline and then decreased to baseline in 1% increments every 10 strides. To verify if leg dominance plays a role in the detection, the distortion was applied to both the dominant (DomAsc and DomDesc) and nondominant legs (N-DomAsc and N-DomDesc). The selection of the distortion range, ranging from 0% to 30%, was determined by conducting four pilot studies. An increase of to 30% was perceived as a substantial distortion that elicited clearly noticeable changes in the avatar's gait patterns without inducing an extremely unstable gait that may induce discomfort or instability. During the initial 10 strides of each condition, no distortion was applied (0%). For every condition, three consecutive trials were executed, which lasted 5 min per trial. The treadmill was not stopped between trials. At the end of each trial, when the maximal distortion level was reached, participants were instructed to keep walking while looking at the avatar's head in the virtual mirror for 30 s. During this time, the distortion applied to the step length of the avatar was suddenly returned to 0% (ascending conditions) or 30% (descending conditions), and the next trial was initiated.

A 10-min break was given between each condition. Before the start of each condition, a 1-min washout period was imposed to avoid any possible adaptations due to exposure to the step length distortions (Kim & Krebs, 2012; Lauzière *et al.*, 2014). During the washout period, the step length of the avatar was not distorted and participants were instructed to observe their avatar by looking down at their body and in the mirror while walking.

4.4.5.3 Detection threshold

To evaluate the detection threshold, participants were instructed to pay attention to the gait of their self-avatar and inform the experimenter as soon as it was accurately replicating their own gait (descending conditions) or no longer accurately replicating their gait (ascending conditions). The specific instructions given before the ascending conditions (DomAsc/ N-DomAsc) were: “Let us know when you feel that avatar is no longer walking as you are.” This instruction was inverted for the descending series (DomDesc/N-DomDesc): “Let us know when you feel that the avatar is walking as you are.” The detection task was completed while walking, and participants verbally responded with “Now”. The point of detection was recorded during each condition. The step length of the avatar continued to increase or decrease after the reported detection point until the minimum distortion of 0% (DomDesc/N-DomDesc) or the maximum distortion of 30% (DomAsc/N-DomAsc) was reached.

To better understand what visual information participants used to detect the step length distortion, participants were asked to answer the following question in between each condition, during the break (hereinafter referred to as the “Symmetry detection questionnaire”); “What type of information did you use to judge the asymmetry (DomAsc/N-DomAsc)/symmetry (DomDesc/ N-DomDesc) between you and your avatar?.” The answers were categorized. Participants could answer from one or more of nine multiple-choice options: trunk flexion, hip flexion, hip extension, heel strike, knee flexion, knee extension, ankle flexion, ankle extension, and other.

4.4.5.4 Sense of embodiment

To assess the subjective feeling of embodiment across different distortion levels in-real time, an additional question was asked at 3% intervals during each condition. This interval was determined to be adequate based on insights gained from four pilot trials. Asking the question at a 1% interval proved too frequent and would potentially divert attention away from observing the avatar’s gait. The participants were asked to rate their agreement with the following statement from 0 to 7: “I feel that the virtual body is my own body,” where 0 indicates strong disagreement and 7 indicates strong agreement. Participants responded to the question verbally while walking. This approach allowed for monitoring of the progression of the SoE throughout the experiment, across different distortions. The embodiment question and detection task were explained prior to the first condition to ensure that participants understood them correctly.

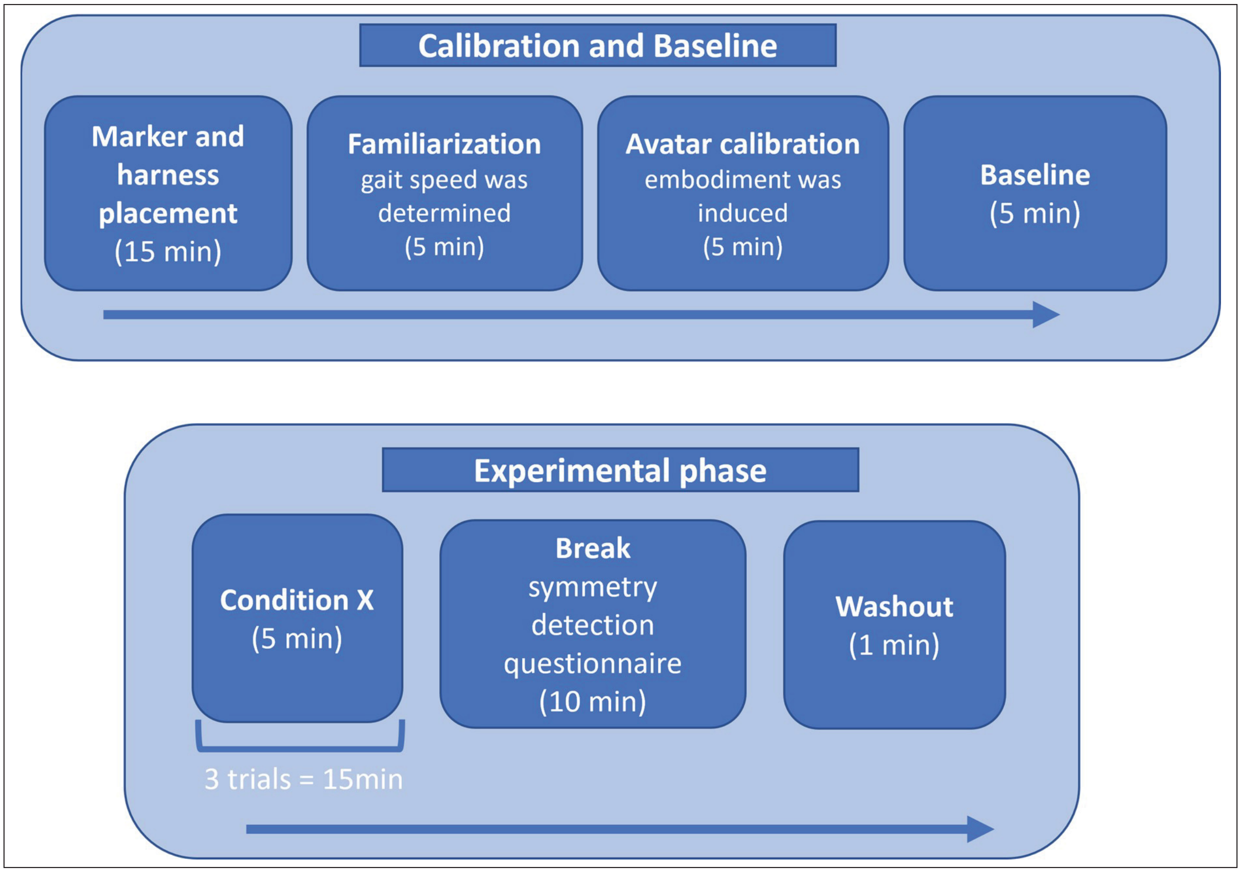

Figure 4.3 Schematic overview of the protocol. Conditions X represents all four conditions DomAsc, N-DomAsc, DomDesc and N-DomDesc.

4.4.6 Data analysis

4.4.6.1 Detection threshold

The detection threshold of each participant was obtained by averaging the point of detection (distortion %) of the three trials, in each of the four conditions (DomAsc, N-DomAsc, DomDesc, N-DomDesc). A linear mixed-effects model (LMM) was employed to analyze the data, with dominance (dominant and non-dominant) and direction (ascending and descending) as fixed effects to account for the main effects and interactions. Additionally, these predictors were treated as random intercepts and slopes, accommodating the variability associated with individual observations and accounting for the repeated measures design. The assumption of normality for the residuals was accepted based on the Shapiro-Wilk test (W = 0.98, p = 0.31) and assessing the QQ plots.

In the absence of a significant main or interaction effects for dominance, suggesting that dominance does not significantly affect the detection threshold, the data for the dominant leg and the non-dominant leg conditions were grouped together, resulting in only two conditions: ascending (Asc) and descending (Desc), each comprising six trials in total. To assess if there were significant differences between the detection threshold of both conditions, a paired sample T-test was applied for pairwise comparison analysis.

The coefficient of variation (CV) was calculated to assess intersubject variability in the detection thresholds. Furthermore, responses from the symmetry detection questionnaire were analyzed by calculating the percentage of participants who selected each possible answer within each category for each condition.

4.4.6.2 Sense of embodiment

The embodiment scores were calculated by averaging the embodiment scores of the three trials of each condition and for each distortion level (every 3% increment). Then, the group mean for each distortion level was calculated. To evaluate the impact of the point of detection on the sense of embodiment, a separate analysis was conducted around the point of detection of each participant. The mean embodiment was calculated for each participant at five specific points: at the point of detection (D%), detection +3% distortion (D + 3%), detection +6% distortion (D + 6%), detection -3% distortion (D - 3%), and detection -6% distortion (D - 6%).

For both analyses, two distinct linear mixed-effects models (LMMs) were employed, with direction (ascending, descending), dominance, and distortion levels set as fixed effects to investigate their main effects and interactions. To accommodate for individual variability, each model included random intercepts for participants and allowed the influence of direction, dominance, and distortion levels to vary across individuals by incorporating them as random slopes within each subject.

In light of the absence of significant dominance effects and its interactions, data from the dominant and non-dominant leg conditions were then combined. Subsequently, a revised LMM model was then applied, including direction and distortion levels as fixed effects while maintaining these predictors as random effects and slopes within subjects. The Shapiro-Wilk test and QQ plots indicated that the residuals of both models did not meet the assumption of normality. However, LMMs are known for their robustness in such situations (Schielzeth *et al.*, 2020). Pairwise comparisons were conducted using the Tukey HSD method, which corrected the p-values for multiple comparisons. Lastly, the relationship between the distortion levels and the embodiment score was measured with the Pearson correlation coefficient.

Data processing and analysis were performed using a custom-made program written in MATLAB R2020 (Mathworks, Natick, MA), and statistical analysis was performed in R Core Team (2023) (RStudio, PBC, Boston, MA). The statistical significance level was established at 0.05 for all tests.

4.5 Results

Thirty-five participants completed the study. Four participants contributed to the pilot testing and were not included in the analysis. One participant's data was excluded due to technical issues during the experiment. The remaining 30 participants (10 females, 20 males; 26.1 (±4.1) years; 174.6 (±10.2) cm; 71.6 (±12.2) kg; 3 left-footed) were included in the analysis. The average self-selected gait speed of the participants was 1.20 m/s (±0.1).

4.5.1 Detection threshold

All participants were able to detect the mismatch/match between their own gait and their avatars during all conditions (Figure 4.4). The LMM results revealed that dominance did not have a significant main effect (SE = 0.86, $t87$ = 1.43, p = 0.15), while the direction (SE = 1.28, $t87$ = -2.067, p = 0.04) did have a significant effect. Furthermore, no significant interaction between dominance and direction was found (SE = 0.98, $t87$ = -1.23, p = 0.22). Consequently, trials with the dominant and non-dominant legs were combined. In the ascending condition (Asc), the mean detection threshold across 30 participants was found to be 12.4% (standard deviation (SD) = 4.8%), while in the descending condition, the threshold was 9.2% (SD = 4.6%). The paired sample t-test revealed that the detection threshold during the ascending condition was significantly higher than the descending threshold ($t29$ = 2.75, p = 0.01). The coefficient of variation (CV) revealed that the inter-subject variability of the detection threshold was higher for the descending conditions (50.1%) compared to the ascending conditions (38.7%).

(Figure 4.5) presents the results of the symmetry detection questionnaire for the ascending and descending conditions. Participants used hip flexion (Asc: 88%, Desc 81%) as the most prominent information to judge their symmetry/asymmetry during the ascending and descending condition, followed by hip extension (Asc: 40%, Desc 38%), trunk flexion (Asc: 38%, Desc 33%), knee extension (Asc: 35%, Desc 36%) and heel strike (Asc: 28%, Desc 35%). Eleven participants indicated relying on another type of information than provided (Other option) to judge their asymmetry/ symmetry with the avatar during either the ascending or descending condition.

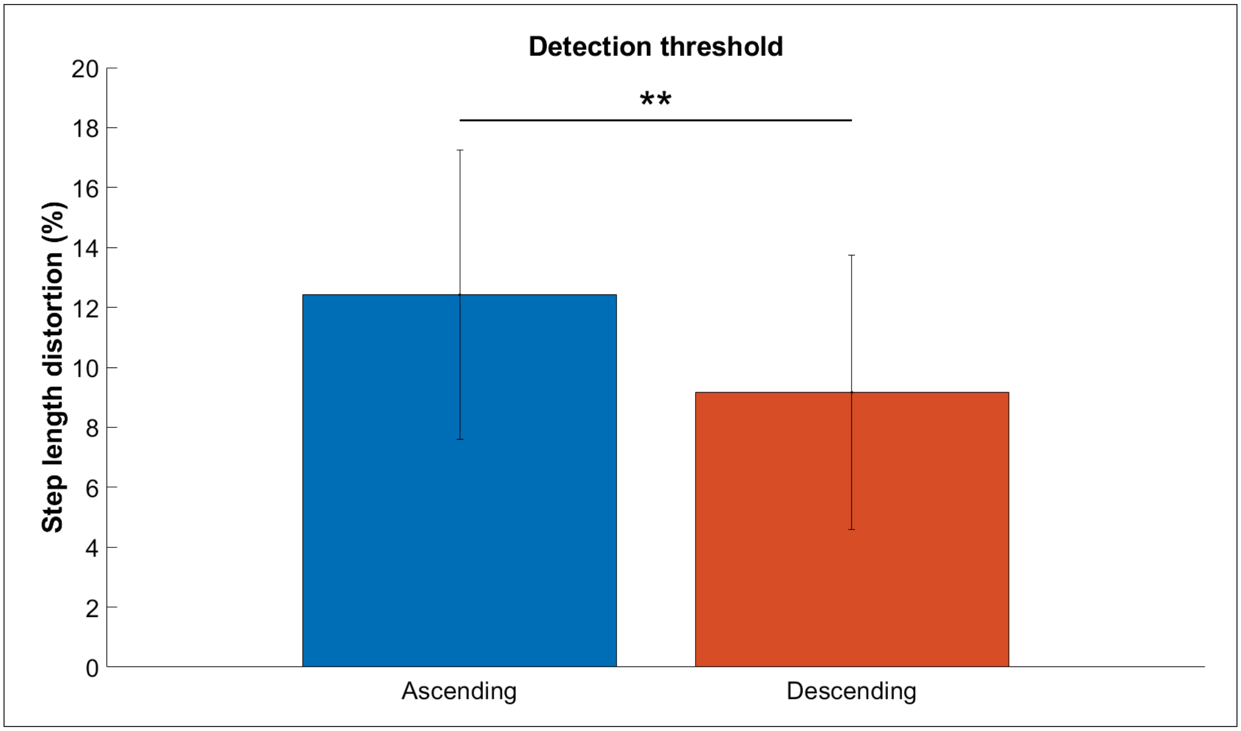

Figure 4.4 Detection threshold: Mean detection threshold in % (N = 30 participants). Error bars represent the standard deviation. **p< 0.01.

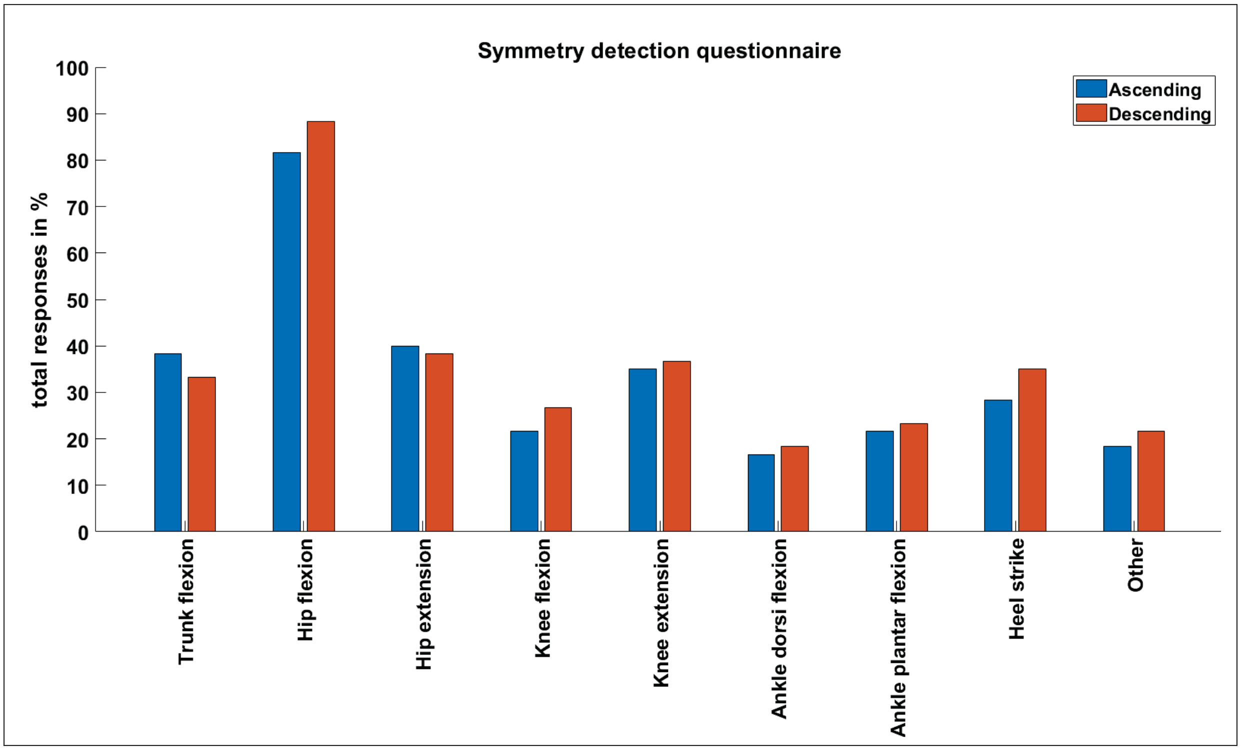

Figure 4.5 Symmetry detection questionnaire: Total of all answers per category in % (N = 30 participants).

4.5.2 Sense of embodiment

The mean embodiment scores are presented in Figure 4.6. Initially, the linear model revealed a significant main effect of the distortion levels on the sense of embodiment (SE = 0.01, $t1{,}283 = -14.35$, $p < 0.001$). However, dominance (SE = 0.23, $t1{,}283 = 0.25$, $p = 0.80$) and direction (SE = 0.23, $t1{,}283 = 0.61$, $p = 0.55$) did not have a significant main effect. As described in the methodology (Section 4.4.6.2), the embodiment scores were aggregated between each leg, resulting in two conditions (Asc and Desc). Within the ascending condition, an increase in distortion levels led to a gradual decrease in the feeling of embodiment from 0% (Mean (M) = 6.3/7, SD = 0.7) to 30% (M = 1.5/7, SD = 1.4). In contrast, the descending conditions exhibited an inverse pattern: as the distortion levels decreased, the feeling of embodiment increased from 30% (M = 1.1/7, SD = 0.6) to 0% (M = 6.3/7, SD = 0.8). The subsequent LMM analysis demonstrated a significant main effect of distortion levels on the sense of embodiment [SE = 0.01, $t627 = -14.90$, $p < 0.001$]. In contrast, the main effect of direction was not significant [SE = 0.21, $t627 = 0.12$, $p = 0.91$], and the interaction effect between distortion levels and direction also did not reach statistical significance [SE = 0.01, $t627 = -1.29$, $p = 0.20$]. Pairwise comparisons revealed significant differences between all adjacent distortion levels in the ascending conditions. Similar findings were observed in the descending conditions. Comparisons between levels that were further apart (e.g., 0% and 6%) were not performed. The Pearson correlation coefficient revealed a significant negative relationship between the distortion levels and the embodiment scores, for both the ascending ($r = -0.82$, $p < 0.0002$) and the descending ($r = -0.84$, $p < 0.0002$) conditions. Figure 4.7 shows the mean embodiment scores for the five specific time points around the point of detection. The LMM did not reveal any significant main effect of dominance, which aligns with the earlier analysis. Consequently, we combined the embodiment scores for the dominant and non-dominant legs for the embodiment scores around the point of detection. The results of the subsequent LMM analysis showed that distortion level [SE = 0.02, $t267 = -11.92$, $p < 0.001$] and direction [SE = 0.18, $t267 = 2.96$, $p = 0.003$] both had significant main effects on embodiment scores. In contrast, the interaction effect between distortion level and direction was not significant [SE = 0.01, $t267 = 0.76$, $p = 0.44$].

The pairwise comparisons further revealed significant differences in embodiment scores between all adjacent distortion levels within the ascending and descending conditions. However, when comparing the embodiment scores at the same distortion levels between ascending and descending conditions, no significant differences were found. These comparisons were specifically conducted at identical levels of distortion to assess the effect of direction (Ascending/ Descending) on embodiment.

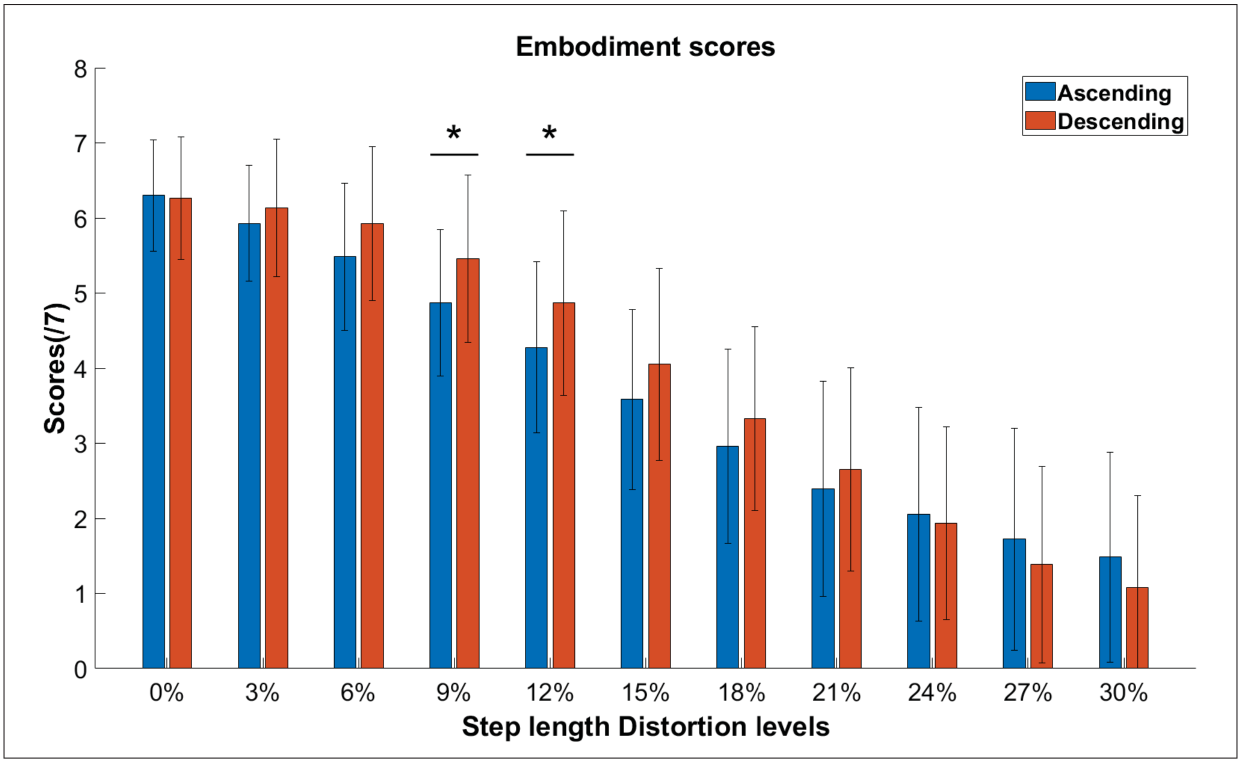

Figure 4.6 Mean embodiment scores at every 3% distortion level. Error bars represent the standard deviation. Note that in the descending condition, the distortions went from 30% to 0%, so the figure is read from right to left for this condition. The significant difference between conditions at the same distortion level is displayed atop the bars. Furthermore, significance was observed between each adjacent distortion level within the same direction (asc or desc). Comparisons between distortion levels that were more distant from each other were not carried out

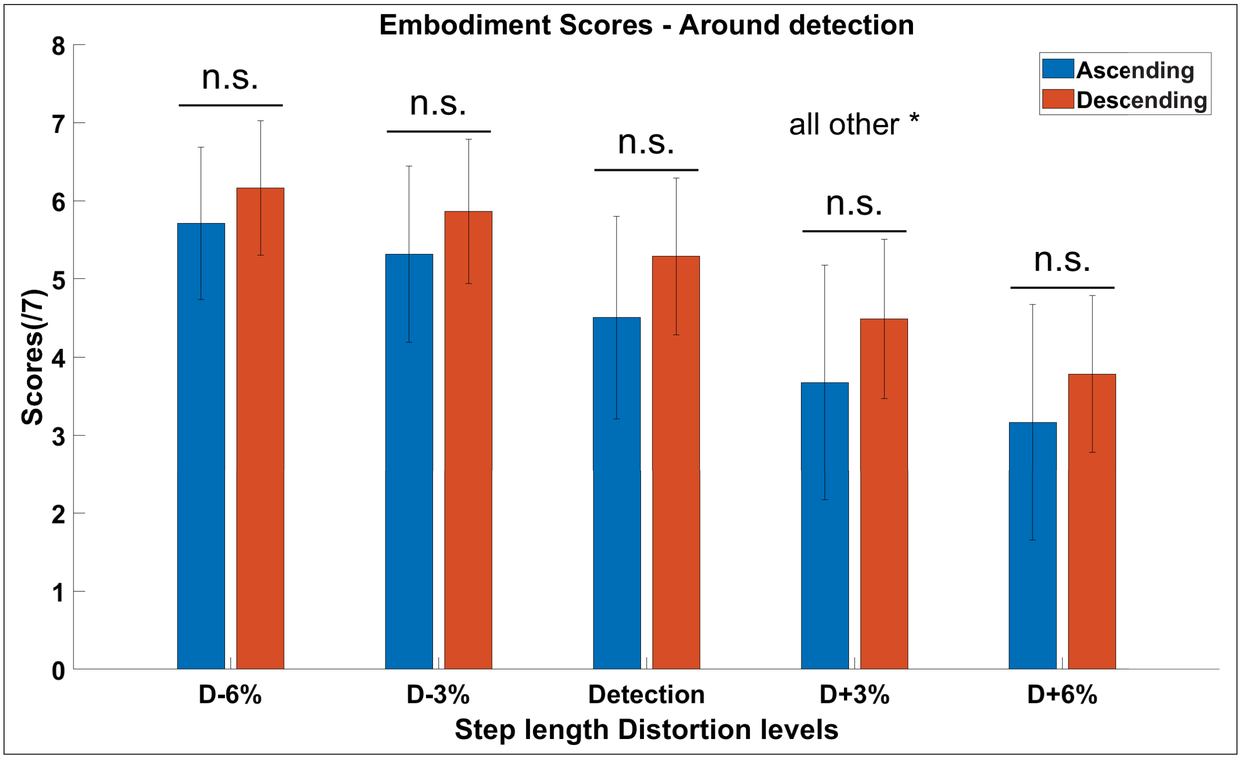

Figure 4.7 Mean embodiment scores around detection, with distortion levels relative to the point of detection. The results for the descending condition were inverted to compare the results with the ascending condition at each distortion level. n.s indicates the absence of significance. All other comparisons were significant. Ascending and descending conditions were only compared at the same level of distortion.

4.6 Discussion

4.6.1 Detection threshold

The first objective of this study was to identify a detection threshold between a participant's actual gait movements and that of their self-avatar, when their step length is unilaterally distorted. The results show that on average, a unilateral increase in the step length of their self-avatar that is below 12% (ascending) and 9% (descending) goes unnoticed by healthy participants. This supports our first hypothesis (H1) that participants would indeed perceive the unilateral distortion in step length as increases that were above those thresholds were eventually perceived.

The limb to which the step length increase was applied did not have a significant effect on the perception threshold. The role of limb dominance within embodiment experiments has primarily been explored in tasks involving the upper limbs. In the well-studied rubber hand illusion (Botvinick & Cohen, 1998), ownership can be induced with similar strength for both the dominant and nondominant hand. However, larger proprioceptive drifts are observed in the nondominant hand (Dempsey-Jones & Kritikos, 2019). This is likely attributed to the frequent use of the dominant hand in fine motor tasks, which tends to rely more on proprioceptive information. Consequently, it may exhibit greater resistance to the false visual information provided by the rubber hand, leading to a reduced drift in the dominant hand. Conversely, relatively little has been studied with regards to the effect of dominance or embodiment on detecting visuomotor discrepancies. The results of this study suggest that limb dominance does not significantly affect the ability to detect gait differences within embodied settings. However, in this study, participants had the contralateral limb available for comparison to detect gait differences in their avatar, unlike in upper body movement contexts where participants could only compare their real arm with the avatar's arm Therefore, it is difficult to establish if the detection was based on the visuoproprioceptive incongruency or the comparison of the movements of both virtual limbs or a combination of both.

Significantly higher detection thresholds were found during the ascending conditions, indicating that participants were less sensitive to the distortion when it gradually increased than when it gradually decreased. Moreover, it is possible that participants were more accurate in the task of identifying the moment where their avatar's movements first matched their own (descending), as opposed to identifying the moment where it no longer matched their own (ascending). However, a study measuring the detection threshold of asymmetry during gait, using a split-belt treadmill, reported higher detection thresholds during the descending conditions (Lauzière *et al.*, 2014). This contrasts with the results found in the current study. In their study, participants walked on a split-belt treadmill with each leg on a separate belt. The speed of one belt was gradually increased until participants perceived a difference in belt speed (ascending threshold), while the descending threshold was obtained by initially setting one belt faster than the other and then gradually decreasing the speed until participants perceived the belt speeds as equal. Nevertheless, a direct comparison of the threshold and symmetry ratios may not be possible due to the different characteristics of the distortions between these two approaches.

In the current study, participants were specifically instructed to detect differences between their avatar's gait and their own, which could have influenced the detection threshold. Therefore, larger distortion may go unnoticed if participants are not instructed to detect or pay attention to potential mismatches between their selfavatars and themselves. Burns *et al.* (2006) found that individuals who were explicitly made aware that a misalignment between their actual and virtual hands would occur, were able to detect a discrepancy of 20°. In contrast, participants who were not provided with this information only became consciously aware of the discrepancy when it reached 40°. Additionally, a study by Galvan Debarba *et al.* (2018) further emphasizes the importance of informing participants about potential mismatches. Their research demonstrated that participants tend to perform poorly in detecting discrepancies during tasks involving reaching for objects in VR when they are not informed about the possibility of a mismatch.

The detection threshold for step length distortion shows considerable variability among participants in both ascending and descending conditions, indicating that individuals have different sensitivities in perceiving these discrepancies. This study obtained the detection threshold by explicitly asking participants to report whether they detected the discrepancies. Previous studies using similar methods within an embodiment distortion paradigm also reported that their detection threshold suffers from a large variability between participants (Galvan Debarba *et al.*, 2018; Porssut *et al.*, 2019; Feick *et al.*, 2022) (Galvan Debarba et al., 2018; Porssut et al., 2019; Feick et al., 2022). Feick *et al.* (2022) suggested that this detection variability may be linked to the participant's previous experience in VR. They found higher thresholds for participants with less experience than those with prior VR experience. A trend toward a higher detection threshold for participants who often play video games has also been reported (Porssut *et al.*, 2022b).

In the subjective detection question, participants reported using similar information to detect the mismatch/match during the ascending and descending conditions. Hip flexion was the information that was most reported to be used to perceive the step length distortion. Participants might have relied on their proprioceptive awareness of hip movement and the visual differences between with the avatar's hip flexion while walking. Indeed, an increase in step length leads to an increase in hip flexion, hip extension, and knee flexion in able-bodied gait (Sawicki & Ferris, 2009; Lim *et al.*, 2017). Therefore, it is plausible that participants noticed the differences between their own actual hip flexion and that of their avatars due to the noticeable increase in hip flexion resulting from the manipulated step lengths.

4.6.2 Sense of embodiment

A second objective of this study was to assess how the different distortion levels and the point of detection impacted the SoE. The results revealed a gradual decrease in embodiment as the distortion levels increased and a gradual increase in embodiment as the distortion levels decreased. The results found during the ascending conditions are consistent with previous research by (Porssut *et al.*, 2019), who also reported a decrease in embodiment when they gradually introduced a discrepancy between the real and the avatar's arm during a reaching task.

The point of detection did not cause a break in embodiment, nor was there a rapid decline seen after the detection. Rather, we observe a steady decline in embodiment as the distortion increases. The level of distortion strongly correlated with the level of embodiment, but the conscious detection of the distortion had no impact on the sense of embodiment. Despite being consciously aware of the distortion, participants still reported feeling embodied in their avatars. This is in contradiction with our second hypothesis (H2), which suggested that the detection of distortion would lead to a break in embodiment.

This finding is consistent with research conducted by Porssut *et al.* (2019) on the upper limb, who similarly found that the detection of a distortion did not disrupt embodiment during an arm movement. However, in their study, a distortion that was gradually introduced and continually increased after the point of detection eventually led to a break in embodiment. Subsequently, the same group of authors found that embodiment remains after a discrepancy is consciously detected, as long as it does not create a visuo-proprioceptive conflict during an arm-reaching task (Porssut *et al.*, 2022a). These conflicts arose when the elbows of the participants reached maximum extension before their avatars did. In our study, similar conflicts did not occur as the lower limb joints did not reach the limits of their ranges of motion during gait. The knee joint comes closest to its limit, and typically reaches a minimum flexion of approximately 5° (Goldberg *et al.*, 2006).

Kannape & Blanke (2013) have previously measured the detection threshold between a users' gait and that of their avatar. Participants were presented with a full-body avatar mimicking their movements in real-time, viewed from a 3rd-person perspective on a large screen that was positioned in front of a treadmill. A temporal delay between the participants' movements and those of the avatar was then gradually introduced. Participants were asked whether they felt their movements were accurately replicated by the avatar. They reported that the sense of agency progressively decreased as the temporal distortion increased, without a clear break in agency at the point of detection. These results are analogous to our results, although they only relate to agency. Embodiment was not measured in that study as the 3rd-person perspective is not conducive to strong feelings of embodiment (Spanlang *et al.*, 2014).

Results from the descending conditions also showed no effect of detection on embodiment. Instead, the level of embodiment shows an inverse relationship with the level of the distortions, and it continued to increase gradually even after the point of detection, where participants reported that the avatar was replicating their gait movements again. When comparing the levels of embodiments at different distortion levels, the directions of the distortions (increasing or decreasing) did not have a significant effect. This indicates that for a given step length distortion, the embodiment level is similar whether that distortion is the result of a large distortion that was gradually decreased or null distortion that was gradually increased.

When a large distortion is initially highly noticeable, it disrupts embodiment, but as the distortion diminishes gradually, participants seem to have adapted to the changes, resulting in the observed trend of higher levels of embodiment. Another factor at play is that, in the descending condition, participants may be evaluating their embodiment relative to the previous distortion level, which was comparatively worse. This comparison might slightly bias the perception of embodiment positively. In contrast, in the ascending condition, the point of comparison is comparatively better, introducing a negative bias to the SoE.

These findings confirm our third hypothesis (H3), which suggests that high levels of embodiment can be established when the avatar's body is initially not spatially aligned with that of the participants, a deviation from the conventional approach to inducing embodiment (Spanlang *et al.*, 2014). Instead, the results of this study demonstrate that certain levels of embodiment can be regained when a very large and clearly noticeable step length distortion is gradually diminished which initially disrupted embodiment. In other words, the direction of the distortion did not appear to play a significant role in the establishment of embodiment. Indeed, previous research indicated that embodiment could be re-established after an abrupt distortion is removed,as such distortions have a negative impact on embodiment (Padrao *et al.*, 2016; Cohn *et al.*, 2020a; Gonzalez-Franco *et al.*, 2020). However, the outcomes of our study suggest that embodiment can also be restored by gradually reducing the magnitude of a substantial distortion while still maintaining visuomotor synchronization rather than solely and abruptly restoring the spatial alignment between the avatar and the participant's movements.

4.6.3 Limitations

A limitation of this study arises from the participants' prior awareness that a distortion towards the gait of the avatar would occur. Although participants were not explicitly informed about the exact nature of the distortion (distortion of their step length), their visual attention was steered to perceive the gait differences of the avatar throughout the experiment. As discussed, this has been shown to lower the detection threshold. Therefore, the thresholds identified in this study may underestimate the size of distortions that would go undetected when users are not aware of potential manipulation of their avatar's movements. Additionally, participants' prior VR experience was not assessed, which previous research has suggested might influence sensitivity to spatial distortions (Feick *et al.*, 2022; Porssut *et al.*, 2022b). Given the reported variability in detection thresholds, it is plausible that prior exposure to VR could have affected our results. Participants with different levels of VR familiarity might exhibit varied thresholds for detecting step length distortions due to differing baseline sensitivities or adaptation skills.

Another limitation of this is that participants' visual attention was directed to the avatar's movements. Healthy individuals typically do not focus on their own feet during gait, which may have affected their natural gait. However, this instruction was necessary to ensure that participants were looking at the gait distortions. Moreover, in a rehabilitation setting, similar instructions would be necessary to ensure that patients accurately observe the avatar's gait distortions. Furthermore, it's possible that participants may have compared the movements of one leg with the other rather than solely comparing their real leg's movements with those of the avatar. This uncertainty presents a limitation since the visibility of both limbs made it difficult to isolate the specific information used to detect the gait asymmetry. Nevertheless, the results remain relevant as they reflect detection thresholds in the context of unilateral step length distortion in applications where these type of manipulations of an avatar's gait would be applied.

Another limitation lies in the methodology for assessing the subjective feeling of embodiment during different distortion levels. An interval of 3% was deemed to be adequate to monitor the progression of the embodiment feeling across the different distortion levels, after conducting four pilot studies. This limitation arose from the practical consideration that requiring participants to continuously respond to the embodiment question at 1% intervals could have been potentially distracting throughout the experiment. Furthermore, due to these constraints, we were not able to employ the validated embodiment questionnaire recently established by (Peck & Gonzalez-Franco, 2021). Instead, a single question was used to assess the embodiment. This question is only one of 16 questions that comprise the Peck and Gonzalez Franco questionnaire, related to the ownership component of embodiment. We therefore have an incomplete measure of the SoE.

Moreover, the repeated measurement of embodiment could have influenced the detection threshold by diverting the participants' attention from identifying discrepancies between the avatar's movements and their own. Individual differences in how participants managed the division of their attention between these discrepancies and the evaluation and reporting of their SoE may partially explain the inter-participant variability in detection thresholds.

4.6.4 Future work

These findings have potential implications for motor rehabilitation, particularly in the context of designing avatars for therapeutic use. They provide a better understanding of the size distortions that can be applied to a self-avatar's gait when aiming for the distortions to go undetected. Avatars can be configured to distort their gait subtly, ensuring that any distortion remains below a predefined detection threshold, such as a 12% increase in step length. This can be done while still preserving a strong sense of embodiment. Similarly, the results show how a given distortion size affects the level of embodiment. If users report a level of embodiment that is below what is required, adjustments can be made to reduce the distortion, effectively increasing the level of embodiment. This approach has the potential to help patients perceive the altered movement as their own, which could ultimately enhance their rehabilitation and recovery (Tambone *et al.*, 2021).

To inform whether the detection of distortions must be avoided and what level of embodiment must be maintained, the complex relationship between the detection of distortions, the subjective level of embodiment, and the strength of resulting motor adjustments should be better understood. Our research provides valuable insights into the relation between the first two elements, shedding light on how extensively we can modify an avatar's gait without it becoming noticeable and how far we can push these distortions while maintaining a relatively high SoE. Further investigation is needed to explore how these factors correlate with changes in proprioception and motor performance, in phenomena like the follower effect (Gonzalez-Franco *et al.*, 2020). Also, when using the paradigm of error exaggeration, the requirements with regard to avoiding detection and maintaining a given level of embodiment may differ.

It is important to note that the detection threshold was obtained with healthy participants. It is possible that the ability to perceive spatial distortion between themselves and their embodied avatar during gait is altered in patients suffering from motor and sensory deficits. Future work should investigate if the detection thresholds for these patients are indeed different from those observed in a healthy population. Although similar detection thresholds were found between healthy participants and mildly ataxic patients with focal lesions in the cerebellum during the split-belt treadmill paradigm (Hoogkamer *et al.*, 2015), the underlying mechanism involved may be distinct from embodied avatar movement distortions protocols.

Lastly, future studies could explore the impact of participants' prior experience with VR on the detection thresholds for self-avatar movement distortions. As our current study did not evaluate participants' VR experience, it remains uncertain whether such experience influenced the observed variability in our results. Therefore, future research could investigate the impact of participants' VR experience, particularly their exposure to VR simulations featuring virtual self-avatars, on the detection thresholds. This exploration could provide additional insights into the factors influencing perceptual thresholds in VR environments.

4.7 Conclusion

Our results show that healthy participants perceive unilateral step length discrepancies that are above 12% and 9% in the ascending and descending conditions, respectively. There is a strong correlation between the level of distortion and the sense of embodiment. As the distortion levels increase, the sense of embodiment decreases, and vice versa. Contrary to the initial hypothesis, the detection of distortion does not break the SoE; participants continue to feel embodied in their avatars even when aware of the distortion. Furthermore, our results show that embodiment can be induced at high levels by gradually decreasing the distortion applied to a virtual self-avatar, rather than the traditional method that consists of inducing embodiment without distortions and gradually applying them. These results provide insights into participants' tolerance for discrepancies in embodied avatar distortion paradigms during gait in virtual environments, with a potential application for motor training and gait rehabilitation.

CHAPTER 5

EFFECT OF UNILATERALLY MANIPULATING THE STEP LENGTH OF AN EMBODIED AVATAR ON GAIT SYMMETRY IN HEALTHY ADULTS

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5.1 Context and contribution

Chapter 5 presents the second article of this thesis and addresses Objective 4. This study builds on the same dataset and experimental protocol as Article 1 (Chapter 4), which focused on the step length distortion awareness and the effect on embodiment. The focus of this article is on whether such distortions lead to measurable motor adjustments, specifically, gait asymmetry, in healthy participants.

This study examines whether participants adapt their own gait to follow the avatar's altered step length, and if so, whether this alignment persists after the distortion is consciously detected. In doing so, it also explores the potential influence of detection threshold and the sense of embodiment on the motor adjustments.

This work builds on previous research on distorted avatar feedback, which has been conducted during voluntary reaching movements involving the upper limb (Gonzalez-Franco *et al.*, 2020; Maselli *et al.*, 2022; Burin *et al.*, 2019; Cohn *et al.*, 2020a). By applying spatial distortions during gait, this study contributes to deepening the understanding of how such distortions affect movement behavior during gait, and how these effects may differ from those observed in prior research focused on upper-limb movements.

5.2 Abstract

In virtual reality, mapping one's body movements to an avatar creates a sense of embodiment, where the avatar is perceived as part of one's own body. Previous studies have indicated that introducing a spatial offset between the avatar's movements and the user's real movements can lead to users unconsciously adjusting their movements to align with the avatar. However, while the effects of such spatial distortion have been studied in the movement of the upper body, little is known about its influence on gait. This study aimed to assess whether altering the step length of an embodied avatar induces a more asymmetrical walking pattern. Thirty healthy participants underwent a treadmill walking experiment while wearing a head-mounted display that displayed an embodied avatar mirroring their movements from a first-person perspective. An algorithm was developed to dynamically increase one of the avatar's step lengths in real-time, introducing gait asymmetry. The effect of step length manipulation on gait asymmetry was assessed under two conditions, where the avatar's step length was gradually increased unilaterally for either the dominant or non-dominant leg. Results indicated that participants did not significantly adjust their gait symmetry to match the avatar's increased step length, whether it was applied to the dominant or non-dominant leg. These findings suggest that healthy participants may be more resistant to visual feedback-induced changes provided by an embodied avatar, in contrast to the adjustments observed in upper-body movements.

5.3 Introduction

Virtual reality (VR) has emerged as a therapeutic tool for the assessment and treatment of patients with neurological conditions who suffer from walking impairments (Porras *et al.*, 2019; Zhang *et al.*, 2021; Keshner & Lamontagne, 2021). Patients with neurological disorders, such as those resulting from a stroke, often face gait deficits that significantly affect their quality of life (Arene & Hidler, 2009; Mayo *et al.*, 1999). Rehabilitation programs typically utilize motor learning principles, focusing on intense, task-oriented, and repetitive training tailored to each patient's specific needs (Belda-Lois *et al.*, 1999). Providing visual feedback during gait has shown to be such an effective interactive method to engage patients during rehabilitation and promote the process of motor learning (Kim & Krebs, 2012; Maestas *et al.*, 2018; Ramachandran & Altschuler, 2009). Research has shown that augmenting visual feedback can influence gait symmetry, even in healthy individuals. For instance, Kim and Krebs (Kim & Krebs, 2012) presented visual feedback on a screen to participants as two separate vertical bars corresponding to the left and right step lengths during treadmill walking in healthy participants. When this feedback was distorted by lengthening one of the bars to create a perceived asymmetry in step length, participants spontaneously adjusted their gait away from symmetry. This adjustment likely occurred due to the fact that the distortion of the bars creates a prediction error between the actual step length of participants and where the bar is displayed on the screen, as the latter is not where it is supposed to be. In response, participants adjusted their step lengths to align them with the displayed feedback (Kim & Krebs, 2012).

Immersive VR environments offer the added possibility to create visual illusions about the body that "bend the truth," delivering real-time altered visual feedback of movements which is not possible in the real world (Porras *et al.*, 2018; Adamovich *et al.*, 2009). Furthermore, virtual bodies or self-avatars can represent the user's body movements inside the virtual environment seen from a first-person perspective position (Slater *et al.*, 2010). As this happens in real-time, the user is in control of the avatar's movements, which can lead to the acceptance of the virtual body as part of their own body and typically creates a sense of embodiment (SoE) over the avatar (Kilteni & Slater, 2012; Kokkinara & Slater, 2014). Extensive research has demonstrated that SoE can be a particularly strong illusion and plays an important role in users' experience within immersive VR (Slater *et al.*, 2008; Banakou *et al.*, 2013; Kokkinara *et al.*, 2016; Peck *et al.*, 2013). More recently, evidence showed that manipulating alignment by introducing a spatial offset between the avatar and the user can affect the user's motor behaviour without breaking the sense of embodiment. This phenomenon, referred to as the *self-avatar follower effect* by Gonzalez-Franco et al. (Gonzalez-Franco *et al.*, 2020), describes how users unconsciously adjust their movements to align with the avatar's altered position. This has been demonstrated in upper body reaching tasks, where participants adapted their movements to mirror the virtual body's misalignment. Moreover, this adjustment occurred spontaneously, without explicit instructions, while maintaining a strong sense of embodiment over the avatar (Burin *et al.*, 2019; Bourdin *et al.*, 2019; Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020a).

These previous studies have shown that users tend to follow their avatars and unconsciously adapt their movements in response to altered avatar movements. However, these effects have mostly been observed during discrete, visually guided upper-limb tasks, such as reaching, where movements are directed toward a visible target. Burin *et al.* (2019), in contrast, demonstrated that this kind of motor interference can also occur during continuous, rhythmic motion. In their study, participants asked to draw straight lines while observing an avatar performing elliptical movements gradually adjusted their trajectories to match the avatar's motion. Importantly, this occurred even in the absence of an explicit target and was stronger when participants reported a higher sense of ownership over the avatar.

To our knowledge, no previous work has explored whether this "follower effect" also applies to gait, a similarly rhythmic and continuous form of movement, but one that typically lacks a visual goal and is governed by different motor control mechanisms. Gait is driven by lower-level control processes, including central pattern generators, and involves the lower limbs (Malone & Bastian, 2010; Clark, 2015), which have been less studied in this context. While the findings from Burin *et al.* (2019) suggest that the follower effect could extend to gait, it remains an open question whether participants will spontaneously adapt their walking patterns to follow distorted avatar movements during locomotion.

This study directly addresses that question. It builds upon our previous work using the same experimental dataset (Willaert *et al.*, 2024), but with a different focus and set of hypotheses, which were defined a priori as part of the original study design. Whereas the first study examined how gait distortions were perceived by participants and how embodiment changed as a function of distortion amplitude, particularly whether embodiment was maintained beyond the point of detection, this paper investigates whether the follower effect, as described by Burin *et al.* (2019)

and others, can be observed in the context of gait. Specifically, we examine whether participants follow changes in the avatar's step length, and how the level of embodiment may influence the extent to which they adapt their own gait in response.

A virtual environment was developed in which participants walked on a treadmill while embodied in a full-body avatar whose step length was altered. The step length distortion was applied unilaterally, targeting both the dominant and non-dominant legs separately. Both were studied as prior research has highlighted that limb differences exist during able-bodied walking, potentially influenced by limb dominance (Sadeghi *et al.*, 2000). Additionally, proprioceptive acuity has been shown to differ between the dominant and non-dominant lower limbs (Han *et al.*, 2013), suggesting that each leg may respond differently to step length distortions.

It was hypothesized that the gradual manipulation of the avatar's step length would prompt participants to follow the distorted avatar's step length and adjust their own step length, thereby inducing symmetrical gait patterns (H1). Furthermore, in line with previous findings that detection of step length distortions did not affect embodiment (Willaert *et al.*, 2024), we hypothesized that changes in gait symmetry remain past the detection threshold (H2).

5.3.1 Altered visual feedback to guide movement

In a virtual environment where users are in control of a virtual body that mimics their movements through real-time body tracking, a strong sense of embodiment is usually established, where one feels in control of the avatar (Spanlang *et al.*, 2014). However, recent studies have demonstrated that the avatar can significantly influence participants' motor behaviour. This has been observed when the avatar's movements are deliberately altered to create a deviation from what is actually being produced by the users (Gonzalez-Franco *et al.*, 2020; Bourdin *et al.*, 2019; Burin *et al.*, 2019; Berger *et al.*, 2022). For instance, in a study where participants were tasked with drawing straight lines while observing an avatar executing elliptical movements, they tended to unconsciously adjust their movements to resemble the avatar's actions, resulting in drawing shapes more similar to the avatar's ellipses (Burin *et al.*, 2019). This mismatch, where the virtual hand's observed position differed from the real hand's sensory feedback, demonstrated how the avatar's movements influenced motor behaviour, prompting participants to adjust their own movements to align more closely with the avatar. Moreover, these effects were significantly higher when the avatar was perceived as part of their own body, demonstrating these incongruent errors are perceived differently depending on the level of embodiment. Prediction errors become more relevant in the context of sensorimotor reweighting when the avatar's body is strongly perceived as the user's own body (Burin *et al.*, 2019).

A similar phenomenon was observed during a seated arm-reaching task, where participants reached for a visual target while the avatar's hand was snapped to a predefined trajectory, introducing a spatial mismatch of a maximum of 30 degrees in the medio-lateral axis between their real and the avatar's arm movements. Despite not being explicitly instructed to do so, participants unknowingly adjusted their arm movements to align more closely with the avatar's altered position, rather than continuing to reach in a straight line, all while maintaining their sense of embodiment (Gonzalez-Franco *et al.*, 2020). This effect was later extended to vertical offsets, where participants adapted to spatial displacements of up to 15° along the vertical axis (Cohn *et al.*, 2020a). The authors further suggested that observed motor adjustments are a by-product of embodiment. Their findings showed that participants reported higher embodiment when the spatial offset was introduced gradually rather than instantaneously. Greater embodiment was associated with stronger motor adjustments, as participants instinctively aligned their movements with the avatar to minimize the spatial mismatch. In contrast, when the distortion was introduced instantaneously, the resulting sensory conflict reduced the sense of embodiment and reduced the observed motor adjustments, although embodiment was not entirely disrupted due to the preserved visuomotor synchronization between real and avatar movements.

This adaptation phenomenon was also demonstrated in the "Pinocchio Illusion," where participants' real arm movements extended further along the anterior-posterior axis to align with the exaggerated elongation of the virtual arm and nose (Berger *et al.*, 2022). In this study, participants engaged in a task where they repeatedly tapped the virtual avatar's nose. With each tap, the virtual arm elongated by up to 50% of its original length, and the virtual nose gradually extended forward to a maximum of 70 cm, creating the illusion of artificial lengthening. Moreover, this effect was strongly influenced by the synchrony of feedback: when visual and proprioceptive feedback were synchronized in real-time with participants' tapping movements, a stronger sense of ownership over the virtual arm, which was accompanied by more pronounced drift in their real arm movements. In contrast, asynchronous feedback, introduced by delaying the visual elongation relative to the participant's tapping, diminished the illusion of embodiment and reduced the observed motor adjustments.

High embodiment scores for ownership and agency were also observed during an elbow flexion task where the avatar's arm movement amplitudes were modulated. In this study, participants were instructed to bring their elbow to a 90° flexion while the avatar's arm flexion was altered without their explicit knowledge (Bourdin *et al.*, 2019). When the participant's real arm reached the 90° position, the avatar's arm was either modulated to 75° (-15°) or 105° (+15°) with respect to the real arm. Results indicated that when the avatar's arm showed a reduced range of motion (75°), participants compensated by increasing their actual elbow flexion. Conversely, when the avatar's arm displayed an over-extended range of motion (105°), participants responded by decreasing their real elbow flexion. These findings suggest that altered visual feedback, when experienced with a strong sense of ownership, can significantly influence motor performance.

The motor compensation observed in these above-mentioned studies (Burin *et al.*, 2019; Bourdin *et al.*, 2019; Berger *et al.*, 2022; Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020a), may be explained by the theories of motor control particularly those involving the forward model inherent in voluntary motor control (Welniarz *et al.*, 2021;

Miall & Wolpert, 1996). The introduced spatial offset creates a disparity between the predicted limb position (actual limb positions) and the visual information provided by the avatar's position. This mismatch likely triggers a sensory conflict, compelling the nervous system to minimize the error by adjusting limb movements to align more closely with the visual feedback (Maselli *et al.*, 2022). Interestingly, in these studies (Burin *et al.*, 2019; Bourdin *et al.*, 2019; Berger *et al.*, 2022; Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020a), participants were generally unaware of their adjusted motor performance but consistently reported high levels of embodiment. As suggested by the authors, when actions produce unexpected results, as observed in these tasks (such as an altered embodied avatar), the brain updates its internal models to reduce prediction errors while preserving a coherent sense of the body. These adjustments are driven by the need to resolve sensory discrepancies rather than intentional action, which may explain why they are not consciously perceived (Maselli *et al.*, 2022). Moreover, Burin et al.Burin *et al.* (2019) demonstrated that these motor adjustments can occur even when participants are explicitly aware of the experimental manipulations. This finding may imply that conscious awareness may be more closely tied to intended actions than to actually executed movements.

Moreover, the motor adjustments observed in VR embodiment settings when exposed to spatially offset avatars may offer possible implications for motor rehabilitation. By providing real-time, distorted visual feedback, therapists can present patients with customized manipulations of their avatar's movements tailored to specific therapeutic goals (increasing range of motion or improving gait symmetry). This approach can be utilized to intentionally amplify errors made during motor tasks, highlighting movement discrepancies to enhance awareness and promote cognitive engagement in correcting those errors (Gaveau *et al.*, 2014; Fasola *et al.*, 2019). Alternatively, the avatar's movements can be programmed to align more closely with the intended motion, guiding patients toward improved motor performance. In the context of gait rehabilitation, where abnormalities such as step length asymmetry are commonly observed (Balasubramanian *et al.*, 2007; Olney & Richards, 1996), an avatar's step length can be strategically exaggerated or reduced in real time to encourage patients to adjust their own step length in response, promoting gait symmetry. However, to effectively apply such interventions, it is crucial to first understand how healthy individuals respond to step length distortions and whether they adjust their gait symmetry.

The effects of spatially offset avatars on motor adjustments have primarily been studied in upper-body movements, particularly in the context of reaching tasks. Although prior studies have demonstrated that lower-limb motor behavior can be influenced by self-avatar movements, these effects were primarily observed in the context of temporal mismatches or decision uncertainty rather than spatial distortions (Boban *et al.*, 2024, 2023). For instance, Boban and colleagues showed that participants unintentionally synchronized their stepping with a temporally delayed avatar and were influenced by avatar errors during memorized movement sequences. However, research investigating motor adaptation to spatially distorted lower-limb avatar movements, especially during gait, remains limited. This gap in the literature highlights the need to examine whether the mechanisms of adaptation observed in upper-limb tasks also occur during gait in response to spatially distorted avatar movements. While upper body movements are voluntary actions guided primarily by visual and proprioceptive feedback, the lower limbs are predominantly engaged in gait, a rhythmic and complex motor behaviour coordinated by the nervous system, which relies more heavily on proprioceptive and vestibular input (Hajnal *et al.*, 2007). These fundamental differences suggest that adaptation phenomena, such as motor adjustments in response to spatial offsets, may manifest differently during gait.

5.4 Methodology

5.4.1 Participants

Thirty participants with no lower limb injuries that affected their gait volunteered to take part in this study. Lower limb dominance was established by instructing participants to kick a foam ball toward the wall, and the foot they naturally used for the kick was considered their dominant one. Three participants were left-footed. Ethical approval for the study was obtained from the ethics committees of CHUM (Centre hospital université de Montréal) and ETS (Ecole de technologie supérieure), and all participants provided written consent before the start of the experiment.

5.4.2 Materials

Participants were asked to walk on a split-belt treadmill (Advanced Mechanical Technology Inc, Waterdown, MA, USA) with both treadmill belts tied at all times. A safety harness was used to prevent and support their weight in the event of a fall due to loss of balance while walking on the treadmill for the duration of the entire experiment (Figure 5.1). Kinematic data, recorded at a sampling frequency of 200 Hz, were collected using a 12 Vicon T20-S system (Vicon Motion Systems Ltd, Oxford, UK). Vicon Tracker 3.6 facilitated real-time data capture, using a 14-marker rigid body cluster attached with Velcro straps to monitor movements of specific body parts (toes, feet, upper leg, pelvis (L5-S1), hands, upper arms, forearms,and upper spine (between the shoulder blades) and the collar bones). For the kinematic analysis, single markers were placed bilaterally on anatomical parts of the body such as the greater trochanter (GT), the lateral epicondyle of the femur (knee) (LEP), lateral malleoli (LM) and on the middle of the heel. Vicon Pegasus Advanced 1.2.2 then retargeted limb positions and orientations onto a virtual avatar displayed in the virtual environment (VE) in real-time. The avatar, created with MakeHuman 1.20 (MakeHuman), was scaled based on participants' body height and weight and gender-matched. Both male and female avatars were outfitted in blue shorts, a grey T-shirt, and blue trainers (Figure 1) Visualized through an HTC VIVE Pro Eye head-mounted display (HMD) with a first-person perspective (1PP) relative to the avatar, the VE featured a replica of the research lab. The lab included a virtual mirror positioned 1.0m in front of the virtual treadmill. Unity 3D (Unity) game engine version 2019.3.13f1 was used to create the VE, ensuring that the virtual treadmill and safety railings matched the dimensions of the real-world environment for a safe walking experience in the VE.

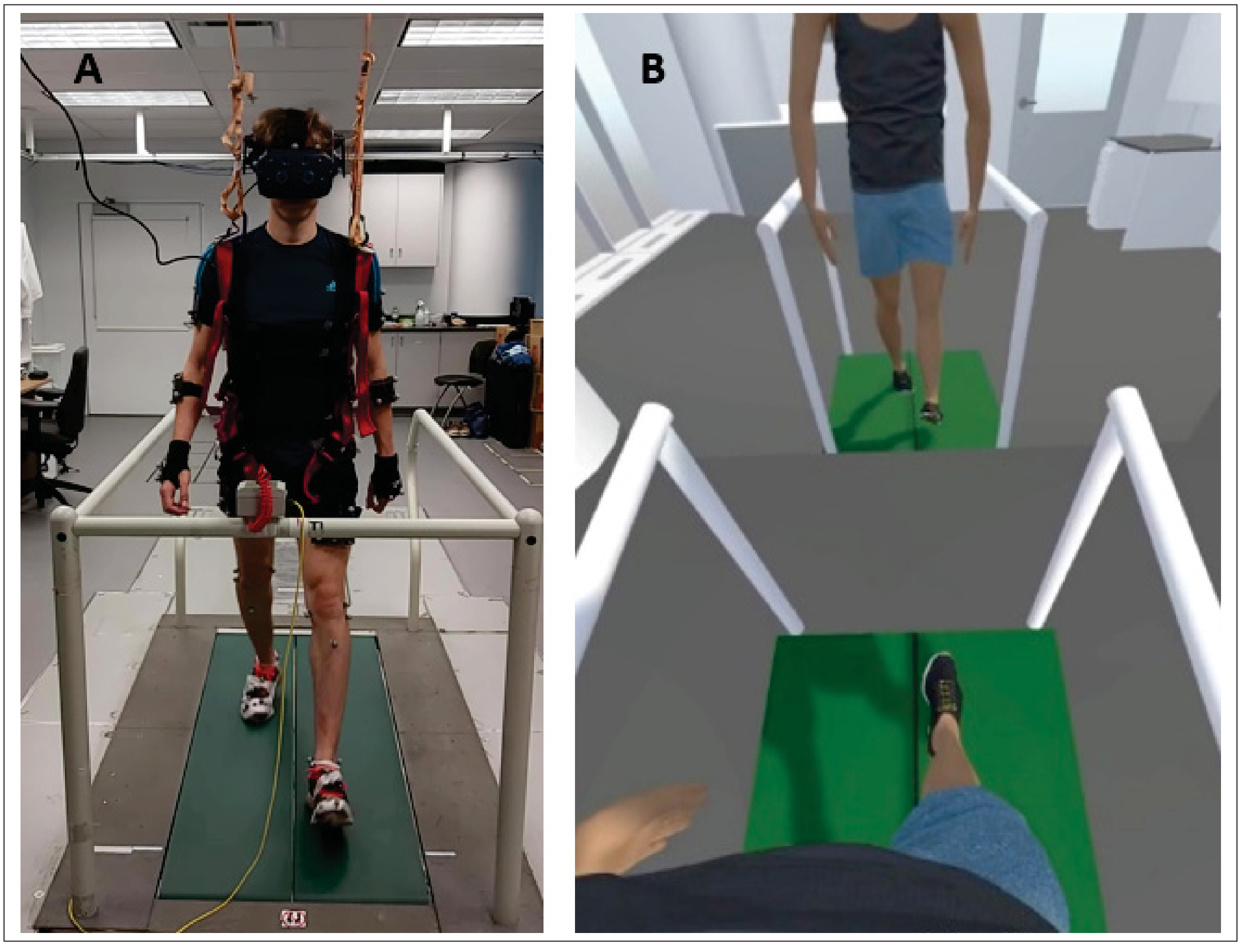

Figure 5.1 Experimental setup. A: A participant walking on the treadmill while wearing the motion capture clusters, the Vive Pro Eye, and the safety harness attached to the ceiling. B: The participant's avatar walking in the VE in front of a virtual mirror, viewed from a first-person perspective.

5.4.3 Gait symmetry distortion model

To introduce asymmetry in the avatar's gait in real time, we implemented an algorithm that progressively modifies the step length of one leg during walking. This manipulation was achieved by applying a time-varying spatial offset between the virtual ankle and the user's actual ankle position along the anteroposterior (AP) axis of the tibia (see Figure 5.2). The magnitude of the offset was defined as a percentage of the participant's average step length, calculated from a two-minute baseline walking trial.

The offset profile followed a gait-phase-dependent pattern. It increased steadily starting from mid-swing, identified as the point where the ankle aligns vertically with the hip during forward leg motion, causing the avatar's ankle to move forward along the AP axis until the moment of heel strike (Figure 5.2A). At heel strike, the offset reversed direction and began decreasing (Figure 5.2B), becoming negative by midstance. This negative offset then increased in magnitude until heel-off (Figure 5.2C), after which it gradually returned to zero by the next mid-swing. The ratio between forward and backward displacements was calibrated individually, based on each participant's maximum anterior and posterior ankle positions relative to the hip.

The resulting movement of the avatar's lower limb was generated using inverse kinematics via the FinalIK plugin (RootMotion). To support the sense of embodiment, the onset of the avatar's (distorted) heel strike remained temporally aligned with the participant's actual heel strike, thereby preserving visuotactile synchrony (Kokkinara *et al.*, 2015).

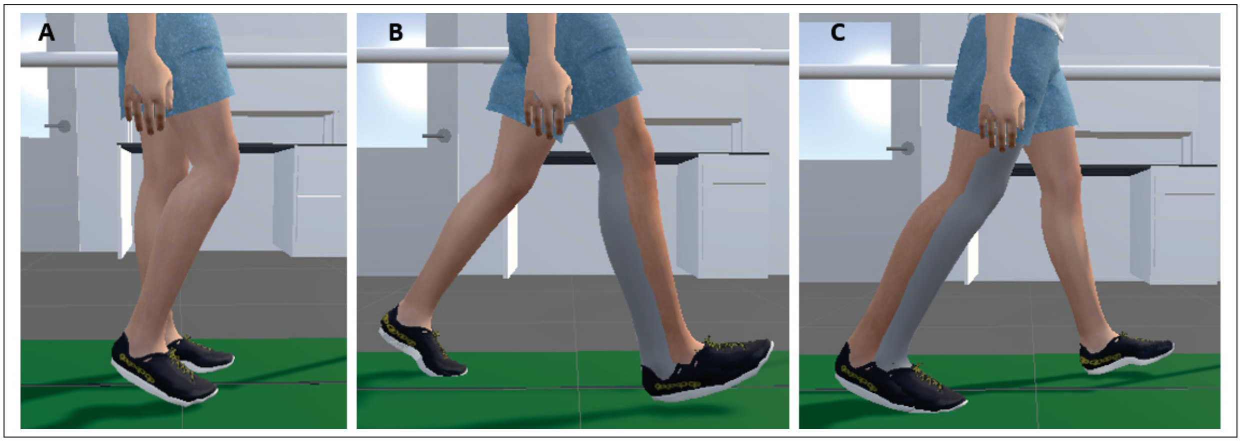

Figure 5.2 Right step length distortion. The translucent avatar represents the participant's actual leg position, and the opaque avatar illustrates the distorted position of the right lower leg. Participants viewed their avatars from a first-person perspective (1PP) and could not see the translucent avatar. A: The avatar's right limb is in mid-swing. At this point, the AP offset of the ankle is zero and begins to increase linearly along the AP axis of the tibia. B: At the moment of right heel-strike, the ankle offset reaches its maximum positive value and then starts to decrease. C: The avatar's right heel lifts off the ground (heel off). The ankle offset reaches its maximum negative value and then decreases, returning to zero offset at mid-swing (A).

5.4.4 Experimental protocol

Participants were invited to perform the experiment in a single session, which lasted 3 hours and 30 minutes.

5.4.4.1 Calibration and baseline

Participants first completed a brief treadmill familiarization lasting approximately five minutes, performed without the HMD. This phase ensured that each participant was at ease with walking on the treadmill, provided an opportunity to verify that the reflective marker clusters remained secure, and allowed the determination of a comfortable walking pace. The belt speed began at 1 m/s and was adjusted in increments of 0.1 m/s until participants confirmed that it matched their preferred pace.

Once this preliminary stage was complete, the HMD was fitted and the avatar's position aligned to the participant's body using the Vicon Pegasus Advanced system. During calibration, participants were asked to stand upright with feet pointing forward, arms relaxed at their sides, and their gaze directed straight ahead. The virtual body was kept hidden during this process to prevent exposing participants to potential visual discrepancies.

After calibration, participants engaged in a 1-minute movement phase designed to induce a sense of embodiment. They alternated between looking down at their limbs and observing themselves in the virtual mirror while performing upper and lower limb movements. Prior work has shown that such active visuomotor engagement can enhance the feeling of ownership over a virtual body (Kokkinara & Slater, 2014). Subsequently, participants completed a 5-minute treadmill walk while wearing the HMD to familiarize themselves with ambulation in the virtual environment (VE). During this walk and throughout the experiment, participants were instructed to shift their gaze between their virtual body in the mirror and a downward view of their limbs to ensure visibility of the gait manipulations. They were asked to refrain from using the treadmill's handrails and to notify the experimenters immediately in case of discomfort or symptoms such as dizziness or nausea.

The final two minutes of this baseline walk were used to record step length, calculated as the distance in the anteroposterior direction between the heels of the leading and trailing foot at heel contact.

5.4.4.2 Experimental phase

The effects of step length manipulation on gait symmetry were assessed over two different conditions: Dominant-Leg Distortion and Non-Dominant-Leg Distortion. These conditions were pseudo-randomized across participants and lasted approximately 15 minutes each.

In both conditions, the avatar's step length on the manipulated side was progressively altered in 1% increments every 10 strides, reaching a maximum distortion of 30%. Each distortion level lasted for about 10 seconds. The experimental protocol included both ascending trials (0% to 30%) and descending trials (30% to 0%). Only the ascending trials are analyzed in the present study, as they were specifically designed to assess motor adaptation to gradually increasing step length distortion. The descending trials, focused on perceptual thresholds and embodiment, were reported separately (Willaert *et al.*, 2024). Both analyses stem from the same protocol, which was originally designed to address both perceptual and motor aspects of gait distortion under embodiment.

Each condition consisted of three trials, with each trial lasting 5 minutes. A verbal indication was provided to indicate the end of one trial and the start of the next trial. The instructions given to the participants were to look at the avatar's head in the mirror after the completion of all levels of distortion. Following this, the avatar's step length returned to 0%, and the following trial started without stopping the treadmill between trials. The distortion range

(0% to 30%) was selected based on insights from four pilot studies. A 30% increase was a substantial distortion at which the avatar's gait manipulation became clearly noticeable to participants without inducing an extremely unstable gait that may induce discomfort or instability. A 10-minute break was provided between each condition. Additionally, a one-minute washout period was implemented at the beginning of each condition to minimize any potential gait adaptations following exposure to step length distortions (Kim & Krebs, 2012; Lauzière *et al.*, 2014). Throughout the washout period, the step length of the avatar remained unaltered, and participants were instructed to observe their avatar by looking down at their body and in the mirror while walking.

5.4.5 Data analysis

Data analysis for step length, gait symmetry ratio and joint angles was conducted with a custom-written script in MATLAB R2023b (MathWorks, Natick, MA). All statistical analysis was performed in R Studio (version 2023, RStudio, PBC, Boston, MA). The statistical significance level was set at 0.05 for all tests.

5.4.5.1 Gait symmetry

The step length was calculated separately for the dominant and non-dominant legs for each participant across the three trials in both conditions. An average step length was determined for each distortion level (10 steps per distortion level) for both the dominant and non-dominant legs. Subsequently, these average step lengths per distortion level were aggregated to compute an overall mean step length, reflecting data from all participants. To account for individual variations, the step length was normalized by dividing it by the respective leg length of each participant. To further investigate the effect of distortion on gait, a gait symmetry ratio was obtained by dividing the step length of the dominant over the non-dominant leg. A ratio of 1 indicated perfect symmetry.

A Linear Mixed Model (LMM) was used to evaluate the impact of distortion levels on step length and gait symmetry ratio. Separate models were fitted for the step length of the dominant leg and the step length of the non-dominant leg, as well as for the gait symmetry ratio. Each model included two predictors as fixed effects to analyze both main effects and interactions: the Manipulated leg (the avatar's leg to which the distortion was applied) and the Distortion level. To reduce the number of comparisons between each distortion level, the distortion levels were analyzed at 5% intervals (0%, 5%, 10%, 15%, 20%, 25%, and 30%). Following the LMM analysis, the Spearman correlation coefficients were calculated separately for each condition and for each step length (dominant and non-dominant) to explore the relationship between distortion levels and step length within both conditions. The Shapiro-Wilk test was used to assess normality and was rejected (step length of the dominant leg; $W = 0.95$, $p = 0.0001$; step length of the non-dominant leg; $W = 0.95$, $p = 0.0001$).

5.4.5.2 Joint Angles

The hip joint flexion angles were calculated by determining the angle between the thigh segment (consisting of GT and the LEP marker) and the pelvis rigid body. The angle between the thigh and shank segments determined the knee joint angle. The shank segment was defined using markers on the LEP and LM markers. The ankle joint angle was calculated by the angle between the shank and the foot segments, with the foot segment defined by the LM marker and toe rigid bodies (placed in the middle of the phalanges). All joint angles were calculated in the sagittal plane. Lower limb joint angles for the hip, knee, and ankle were calculated for each gait cycle. Similar to the gait symmetry analysis, an initial average was calculated for each participant for each trial and condition across different distortion levels. Subsequently, these individual averages were combined to compute an overall mean across all participants in order to evaluate the impact of the avatar's step length distortion level on joint angles per condition. The peak knee flexion, peak hip flexion, and peak ankle flexion were analyzed to compare joint angles across conditions. Six separate LMMs were employed, one for each of the three lower body joints for both the dominant and non-dominant legs. Each model included the predictor's manipulated leg and distortion levels (0%, 5%, 10%, 15%, 20%, 25%, and 30%). To compare joint angles across conditions, the peak knee flexion (during the swing phase), peak hip flexion (during the swing phase), and peak ankle flexion (during the stance phase) were analyzed.

5.4.5.3 Embodiment

Embodiment scores were collected at each distortion level (0–30%, in 3% increments), where participants verbally rated their sense of embodiment using the statement "I feel that the virtual body is my own body" on a 0–7 Likert scale. The procedure for collecting these ratings has been described in detail in

5.5 Results

Thirty participants completed the study. Data from one participant was excluded due to technical issues during the experiment. The analysis focused on the remaining 29 participants, consisting of 9 females and 20 males, with an average age of 26.1 years (± 4.1), height of 174.6 cm (± 10.2), and weight of 71.6 kg (± 12.2). The participants had an average self-selected gait speed of 1.20 m/s (± 0.1).

5.5.1 Gait symmetry

Figure 5.3 illustrates the overall mean step length across all participants for each distortion level in both conditions. The results of the LMMs analyzed the effects of the Manipulated limb (the limb where the distortion was applied, either the dominant or non-dominant leg of the participant) on the step length of both the dominant and non-dominant legs. For the step length of the participant's dominant leg, there were no significant main effects of the Manipulated leg on the dominant step length (SE=0.002,t(776)=0.15,p=0.87). However, the predictor Distortion level demonstrated a significant main effect (SE=0.00007,t(776)=2.98,p=0.002). Despite this significance, the effect size, as indicated by the marginal R^2 (R^2 = 0.003), was very small, suggesting that the distortion levels had a minimal influence on step length. Additionally, no interaction effects between the two predictors were found. Furthermore, the Spearman correlation analysis indicated no significant relationship between the dominant step length and the distortion levels in the Dominant-leg distortion condition ($\rho = 0.056$, p = 0.10) or the Non-Dominant-leg distortion condition ($\rho = 0.052$, p = 0.12).

For the step length of the participant's non-dominant leg, the LMM results showed no significant main effects for Manipulated leg (SE=0.002, t(374)= 0.09, p = 0.93). However, the Distortion level (SE=0.0001, t(374)= 2.09, p = 0.03) did demonstrate a significant main effect. As with the dominant leg, the effect size was again very small (R^2 = 0.0045). No interaction effects between both predictors were detected. The Spearman correlation analysis revealed no significant relationship between the Dominant-leg distortion condition ($\rho = 0.038$, p = 0.28) or the Non-Dominant-leg distortion condition ($\rho = 0.053$, p = 0.12). Figure 5.4 illustrates the gait symmetry ratio across all the 30% distortion levels for both conditions. The gait symmetry ratio LMM revealed no significant main effects for either the Manipulated leg (SE=0.002, t(374)= -0.35, p=0.72) or the Distortion level (SE=0.0008, t(374)= 0.5, p= 0.55). No significant interaction effects were observed for the gait symmetry ratio. These results indicate that the incrementally introduced step length distortion levels did not significantly influence step length and the gait symmetry ratio across either condition.

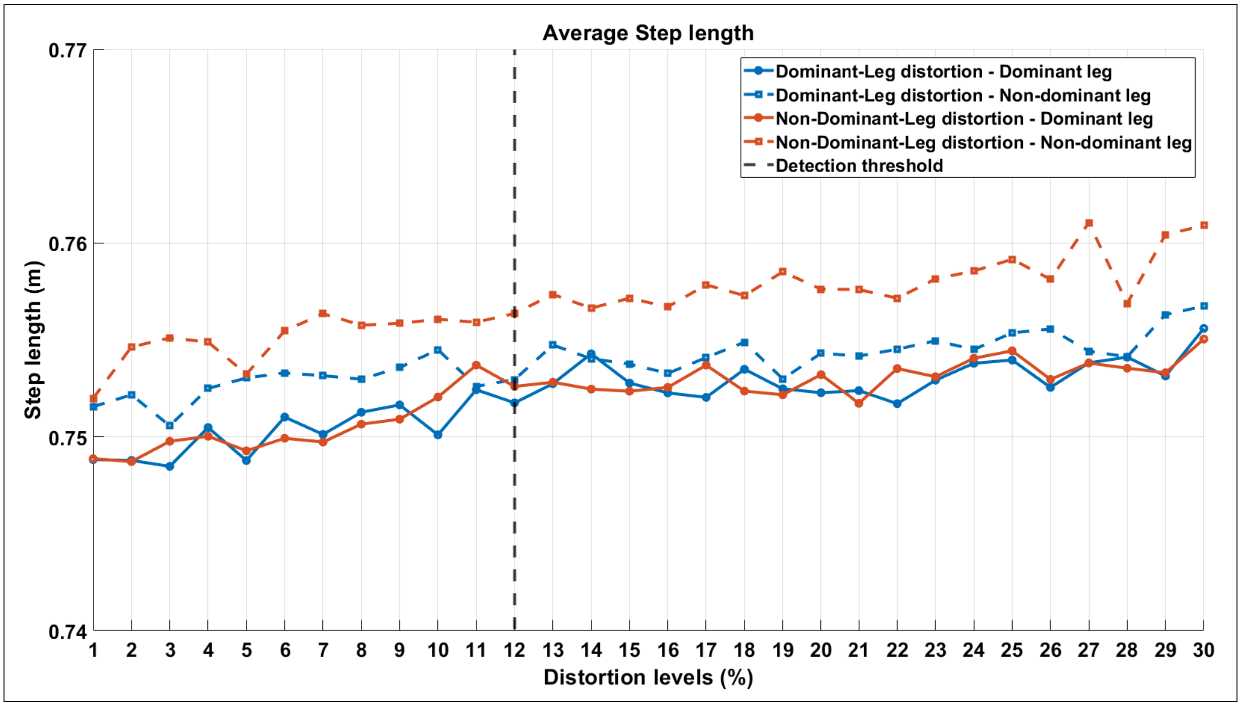

Figure 5.3 Mean dominant and non-dominant step length results across all 30 distortion levels for both conditions, averaged over all participants.

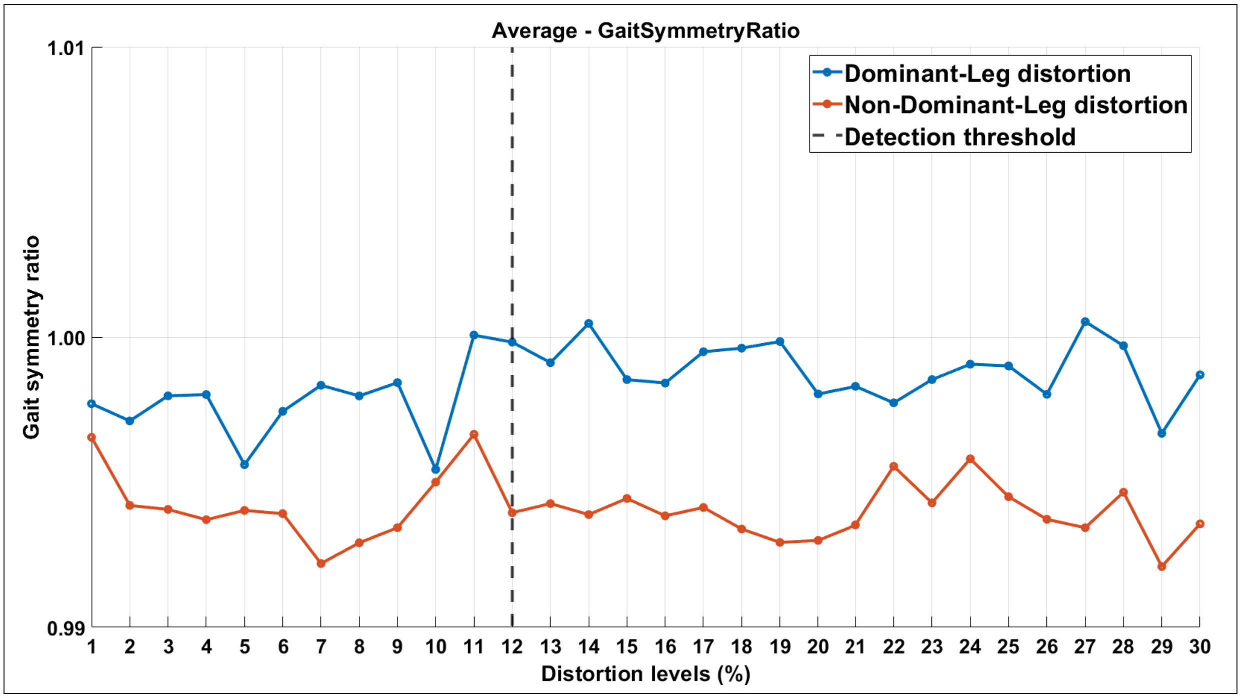

Figure 5.4 Mean gait symmetry ratio results across all 30 distortion levels for both conditions, averaged over all participants.

5.5.2 Joint Angles

For the joint angles analysis, the dataset included data from 20 participants. For 9 participants, specific trials were excluded from this analysis due to issues encountered during data processing because of missing marker trajectories during data capture across all trials. While this resulted in a reduced sample size for the joint angle analysis, the remaining dataset preserved the necessary structure, sufficient valid trials and consistency across conditions to support a robust repeated measures approach. Figures 5.5 and 5.6 illustrate the average joint angles across the gait cycle for the hip, knee, and ankle joints of both the dominant and non-dominant limbs, with Figure 5.5 illustrating the Dominant-Leg distortion condition and Figure 5.6 depicting the NonDominant-leg distortion condition. Different distortion levels are represented by various colours for both conditions.

The results of the linear mixed model (LMM) analysis revealed no significant main effects for the predictors Manipulated leg or Distortion level on peak knee flexion for either the dominant or non-dominant leg, and no interaction effects were observed. Similarly, no significant main or interaction effects were identified for Manipulated leg or Distortion level on peak ankle flexion in both the dominant and non-dominant legs.

For dominant hip peak flexion, while distortion levels (SE = 0.01, t(533) = 0.47, p = 0.63) did not yield a significant main effect, a significant main effect was observed for the predictor Manipulated leg (SE = 0.49, t(257) = 2.78, p = 0.005). However, the effect size, as indicated by the marginal R^2 (R^2 = 0.0061), was very small, suggesting that while statistically significant, the effect has minimal practical relevance within the context of the avatar's step length distortion.

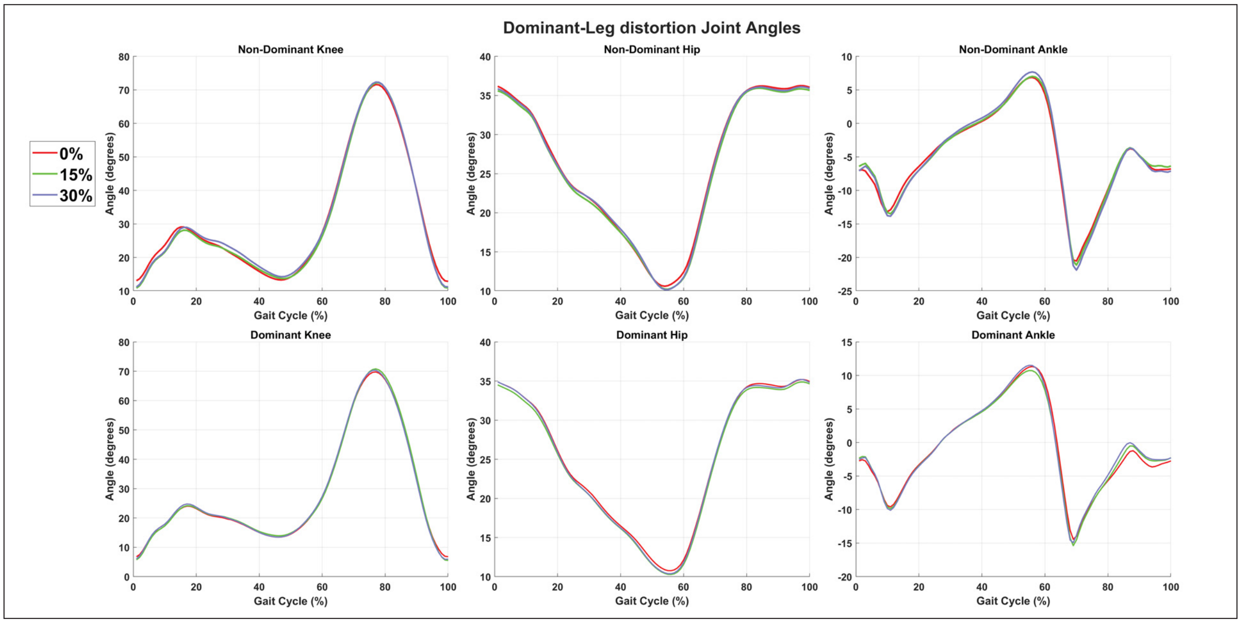

Figure 5.5 Joint peak angles for the knee, hip, and ankle joints across the gait cycles for the condition Dominant-Leg distortion. The results shown are for a single participant and reflect the mean trends. The distortion levels at 0%, 15%, and 30% are represented by different colours.

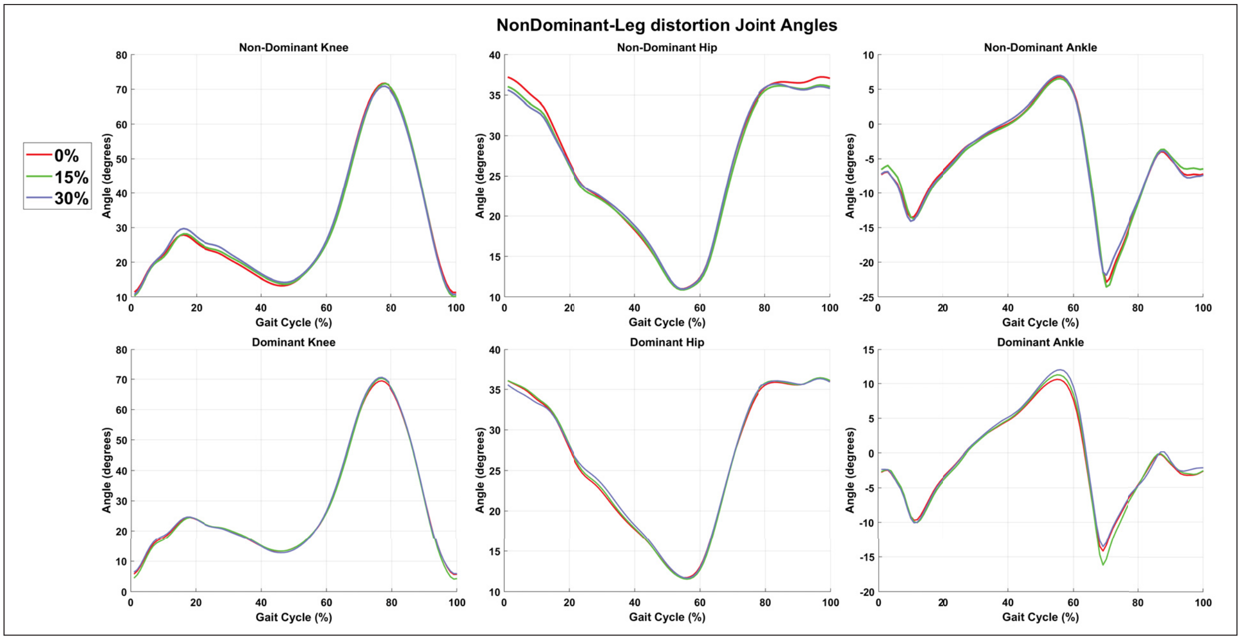

Figure 5.6 Joint peak angles for the knee, hip, and ankle joints across the gait cycles for the condition NonDominant-Leg distortion. The results shown are for a single participant and reflect the mean trends. The distortion levels (0%, 15%, 30%) are represented by different colours.

5.5.3 Embodiment

The results of the LMM analysis revealed no significant association between embodiment ratings and gait symmetry (SE = 0.0001, t(608) = 0.38, p = 0.70). This suggests that variations in the sense of embodiment did not modulate gait behavior when being exposed to step length distortion experienced through an embodied avatar.

5.6 Discussion

5.6.1 Gait Symmetry

The first objective of this study was to evaluate the influence of step length distortion, as presented by an embodied avatar, on the step length of healthy individuals during treadmill walking. Contrary to our initial hypothesis (H1), our findings revealed no changes in gait symmetry among healthy participants during treadmill walking. These findings offer an important extension to prior work by (Burin *et al.*, 2019) who demonstrated that users' motor output could be modulated during continuous, rhythmic movements of the upper-limb. While we did not observe a comparable follower effect in the context of gait, our results highlight how the underlying control mechanisms of gait may limit the extent to which the follower effect generalizes. In this sense, our study complements the work from (Burin *et al.*, 2019) by revealing a potential boundary condition for the follower effect: while rhythmic movement may be sufficient for spontaneous adaptation in upper-limb tasks, the automaticity and proprioceptive dominance of gait appear to resist similar modulation through avatar-based distortions.

Gait is a highly automatic motor task controlled by the central nervous system and central pattern generators, which produce rhythmic coordinated movements without necessitating conscious effort(Malone & Bastian, 2010; Clark, 2015). As described during the studies involving reaching tasks, the discrepancy between the visual information presented (the avatar's altered step length) and the proprioceptive feedback being received from the participant's own body movements potentially created a sensory conflict. However, the findings of the current study suggest that in the context of gait, proprioceptive feedback about the body's real movement and position may have overridden the intrinsic need to accommodate for the visually presented step length changes. In contrast, upper limb movements are often visually guided and rely on continuous sensory feedback and cortical control for fine motor skills and adjustments (Miall & Wolpert, 1996). Visual feedback plays a critical role in guiding precise hand and arm actions during voluntary upper body movements, often carrying greater perceptual weighting than proprioceptive input (Brenner *et al.*, 2023). Thus, the sensory conflict created by the spatial distortion of the avatar may be more influential in visually dominant tasks like reaching than in proprioceptively dominant tasks like gait.

In the current study, the protocol was designed to gradually alter the step length of the avatar over time without the participants' explicit knowledge. Participants were intentionally not instructed to synchronize with or mirror the avatar's step length, allowing us to observe whether gait adjustments would occur spontaneously during treadmill walking. Other studies have also examined the effect of implicitly modified visual feedback in healthy participants, though not through the use of an avatar. These studies reported significant differences in gait symmetry when visual feedback was manipulated using bar graphs that represent, in real time, the step length of each foot(Kim & Krebs, 2012; Tobar *et al.*, 2018). This distortion created a perceived asymmetry, prompting participants to adjust their walking patterns away from symmetry to align with the visual feedback, even without explicit instructions. Although implicit feedback in these studies, delivered through direct visual indicators such as bar graphs, has been shown to elicit changes in gait symmetry, our findings suggest that participants did not spontaneously adapt their gait to follow the trajectory of the avatar's distorted step length in response to visuomotor discrepancies.

Moreover, our earlier results demonstrated that participants were able to consciously detect the step length distortion (Willaert *et al.*, 2024), indicating that the distortion was large enough to create a noticeable prediction error for participants to register the discrepancy actively and to engage sensory systems (Kim & Krebs, 2012; Kim & Mugisha, 2014; Mazzoni & Krakauer, 2006; Taylor *et al.*, 2014). However, the absence of gait modification in response to changes in the avatar's step length suggests that healthy participants, despite being able to perceive the changes in the avatar's step length, did not adapt their walking patterns to align with the avatar.

The second objective of this study was to assess whether the detection threshold influences the changes in gait of the participants in response to the movements of the avatar. The results indicated that the avatar's distortion had no significant effect on gait, and consequently, the detection threshold did not influence gait changes. This lack of changes in gait symmetry supports the rejection of the second hypothesis (H2). Furthermore, findings from our previously reported work demonstrated that the sense of embodiment was negatively correlated with the level of distortion: as the distortion increased, embodiment decreased (Willaert *et al.*, 2024). This suggests that while participants' sense of embodiment was sensitive to the level of step length distortion, gait symmetry remains robust and unaffected.

Lastly, this study involved healthy participants whose gait is optimized for balance and efficiency and appears less susceptible to modification through visual distortions. In contrast, stroke patients, who often exhibit asymmetrical gait patterns and, depending on the lesion location, proprioceptive deficits, tend to rely more on visual feedback (Bernard-Espina *et al.*, 2021; Bonan *et al.*, 2004). As a result, stroke patients might respond differently to interventions involving distorted embodied avatar gait movements. Moreover, previous research suggests that stroke individuals often exhibit a stronger sense of ownership over the affected limb, likely because disruptions in sensory feedback and motor commands reduce their connection to the limb (Burin *et al.*, 2015; Jenkinson *et al.*, 2020). Despite this, similar levels of proprioceptive drift and comparable, though less vivid, embodiment have been observed in stroke patients and healthy individuals in immersive VR settings (Llorens *et al.*, 2017; Borrego *et al.*, 2019). Future studies should investigate how stroke patients respond to avatar-based distorted feedback during gait, designed to address symmetrical gait, and how this affects their sense of embodiment. Exploring the relationship between altered visual feedback provided by self-avatars, the influence on gait symmetry and the sense of embodiment in stroke patients could provide valuable insights for refining and optimizing avatar-based rehabilitation protocols tailored to this population.

5.6.2 Limitations

In this protocol, participants took part in a detection threshold assessment, which required them to identify whether their avatar's gait accurately reflected their own (results published in Willaert et al. (Willaert *et al.*, 2024)). This process may have influenced participants' adaptation to the avatar's movements, as they were made aware of potential distortions in the avatar's gait. Although their attention was directed toward observing differences in the avatar's gait, they were not explicitly informed about the specific distortion in step length. Moreover, healthy individuals do not typically observe their lower body while walking. In our VE, participants could see their entire body, which may have increased their awareness of their movements and potentially disrupted their natural gait.

However, in a rehabilitation setting, similar attention to gait distortions would be necessary to ensure that patients observe the avatar's gait distortions.

Another limitation is that participants walked on a treadmill with fixed speeds, which may have constrained gait by enforcing a consistent pace and reducing natural variability like stopping or pausing. While treadmill walking is widely accepted to represent natural gait in controlled experiments (Lee & Hidler, 2008; Dingwell *et al.*, 2000), these constraints might have limited gait adaptation to the step length distortion. Nevertheless, previous studies have shown that visuomotor adaptation occurs effectively during treadmill walking, with participants on split-belt treadmills adjusting step lengths in response to real-time visual feedback (Sato *et al.*, 2022; Kim & Krebs, 2012; Tobar *et al.*, 2018). Therefore, despite some limitations, the treadmill setup used in this study remains a valid tool for investigating visuomotor adaptation.

5.6.3 Future work

Our recent findings in gait show that the SoE does not significantly break after detecting distortions introduced gradually, indicating that participants still perceive the avatar as part of their body despite the misalignment (Willaert *et al.*, 2024). However, in the current study, without observed gait adjustments, it is unclear how this maintained embodiment influences motor behaviour post-detection. In upper body tasks, where motor adjustments have been observed in response to distortions (Burin *et al.*, 2019; Gonzalez-Franco *et al.*, 2020), exploring the influence of detection thresholds could provide valuable insights into the relationship between sensory awareness, motor adaptation and the SoE. Future research should explore this relationship in tasks where motor adjustments are more evident, such as upper body movements, to determine whether participants actively correct perceived errors (Kusafuka *et al.*, 2022) or gradually adapt their movements to align with the distortion (Abeele & Bock, 2001).

Moreover, it remains unclear how motor adaptation persists in tasks involving lower limb movements when the avatar is spatially misaligned. Ongoing work is investigating how to better understand these dynamics, the effects of the spatial distortion are being examined in lower limb movements under conditions that challenge stability, such as balancing on one leg, to isolate motor responses to avatar distortions. Comparing these effects between the limbs could shed light on differences in the strength of the movement adaptations and the role of the sense of embodiment in these distinct motor tasks.

In the current study, we applied a unilateral step length distortion, creating a visual asymmetry in only one limb. Future studies could investigate whether bilateral distortions that introduce asymmetries across both legs are more effective in eliciting gait adaptation than unilateral distortions. In the unilateral distortion, the non-distorted leg provided a consistent visual reference, which may have led participants to maintain their natural symmetrical gait rather than adjust to the manipulated feedback. This preserved congruence on one side could have reduced the salience of the overall asymmetry, particularly in healthy individuals who had no underlying motor impairment that would necessitate gait correction. In contrast, applying bilateral distortions that introduce asymmetries across both legs may remove this stable reference. Without a congruent side to rely on, the visuomotor conflict may become more pronounced. Testing such configurations would help clarify whether bilateral distortions are more effective at influencing gait behavior in immersive virtual environments.

5.7 Conclusion

This study reveals that healthy gait patterns are resistant to visual distortions introduced by an embodied avatar in a virtual environment. Despite the fact that participants perceived the step length distortions, their gait symmetry remained unaffected, and they did not adapt their movements to align with the avatar's distorted step length. The absence of spontaneous adjustments suggests that the sensory conflict generated by the avatar's distorted step length was insufficient to override participants' reliance on intrinsic sensory feedback, preventing them from following the avatar's movements or disrupting the automaticity of healthy gait. Future research should explore these dynamics in populations with gait impairments, such as stroke patients, who could benefit from tailored rehabilitation protocols incorporating distorted self-avatars.

CHAPTER 6

RESISTING THE AVATAR: MOTOR RESPONSES TO SPATIAL DISTORTIONS IN UPPER- AND LOWER-LIMB REACHING WITHOUT VISUAL TARGETS

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6.1 Context and contribution

Chapter 6 presents the third article of this thesis and addresses Objectives 5 and 6. This study was based on a separate experimental protocol and focuses on how spatial distortions applied to an embodied avatar influence goal-directed reaching movements of the upper and lower limbs.

As the findings of Article 2 revealed that spatial distortions had no measurable impact on gait symmetry, this study aimed to explore whether spatial distortions would affect more deliberate, goal-directed movements. Moreover, prior research showing that participants tend to align with the avatar's distorted trajectory has typically involved visible targets. In contrast, this study removed any explicit visual target, requiring participants to reconcile the visuomotor ambiguity between their actual movements and the avatar's altered trajectory. In addition, this study also examined how increasing postural demands, by requiring participants to perform lower-limb reaches while balancing on one foot, might modulate their response to distortion.

This study contributes to a broader understanding of how spatial distortions affect reaching movements of the upper and lower limbs without visual targets, providing new insights into how such embodied distortions influence motor behavior in immersive virtual environments.

6.2 Abstract

Avatars can represent an individual's body within a virtual environment, mirroring their movements in real-time. When these movements are closely synchronized with those of the user, a sense of embodiment over the avatar is often experienced. Recent research shows that introducing spatial offsets between a user's real movements and those of their avatar can alter motor behavior, with users aligning with the distorted avatar. While previous studies have typically focused on upper-limb movements toward visual targets, it remains unclear how users respond to distortions without such targets, particularly during lower-limb tasks where postural demands may impose constraints. This study examined whether users adjust their movements to follow their distorted avatar during upper- and lower-limb reaching without visual targets. Twenty-four participants performed reaching tasks while their avatar's movements were spatially offset. Results revealed that participants counteracted the avatar's distortion by moving in the opposite direction in both limb tasks. These findings suggest that, in the absence of explicit visual targets, participants treat spatial distortions as execution errors and prioritize internal movement goals over minimizing sensory conflict. This suggests that adaptation depends not only on a strong embodiment but also on whether the task performance permits reducing the mismatch between the user's and the avatar's movements.

6.3 Introduction

In immersive virtual reality (VR), avatars can visually substitute a user's body, providing a representation within the virtual environment. With full-body tracking, the avatar can synchronously mirror the user's real-world movements. Viewing the avatar from a first-person perspective (1PP) can create the illusion that the user's physical body has been replaced by a virtual one. This strong connection between the user and their avatar is referred to as the sense of embodiment (SoE), which is typically defined as comprising three primary components; body ownership (feeling of owning the virtual body), agency (feeling of having global motor control and initiate and control movements of the avatar) and self-location (feeling of being located within the virtual body) (Kilteni & Slater, 2012). Although high temporal synchronicity is critical for establishing and maintaining the illusion of embodiment (Maselli *et al.*, 2015; Kokkinara & Slater, 2014), recent studies suggest that spatial alignment is less crucial, as the sense of embodiment (SoE) can be preserved despite discrepancies between the user's movements and the avatar's motions (Porssut *et al.*, 2019, 2022a; Willaert *et al.*, 2024).

In static conditions, participants often experience a shift in the perceived position of their limb toward a displaced fake or virtual limb. This phenomenon, known as proprioceptive drift, is well-documented in the Rubber Hand Illusion (RHI), where synchronous visuotactile stimulation leads participants to perceive a fake hand as their own while also mislocalizing their real hand (Botvinick & Cohen, 1998; Fuchs *et al.*, 2016; Slater *et al.*, 2008). This shift in perceived limb position is thought to result from the need to resolve multisensory discrepancies arising from conflicting visual, proprioceptive, and tactile input. Asai (2014) demonstrated that this effect is not purely perceptual but has an active component. When the real hand is placed on a moveable board during the RHI, a physical drift can occur, where the real hand tends to move toward the fake hand. Building on these findings, Lanillos *et al.* (2021) demonstrated that in a virtual hand illusion, participants not only experienced perceptual drift but also exerted involuntary forces in the direction of the virtual hand, further supporting the idea that these actions could emerge as a response to minimize multisensory conflicts.

In conditions where participants control a full-body avatar, applying spatial distortions has been shown to influence motor behavior. For instance, in a goal-directed reaching task towards a visual target, where the avatar's movement is snapped onto a predefined trajectory, participants alter their reaching movements to align more closely with the trajectory of the avatar, despite not receiving explicit instructions to do so (Cohn *et al.*, 2020b; Gonzalez-Franco *et al.*, 2020). It is worth noting, however, that in tasks involving a visual target, the avatar's altered movements were still oriented toward the intended goal. As such, part of the observed motor adaptation could reflect participants' attempts to align their real movements with the visual target itself, rather than a pure tendency to follow the avatar's movements. In continuous movement tasks, such as when participants attempt to draw straight lines back and forth while their avatar is programmed to draw ellipses, they unconsciously adjust their own movements, producing oval shapes instead of straight lines (Burin *et al.*, 2019). These findings suggest that when users control an avatar under spatial misalignment, they actively adjust their movements towards the virtual limb to reduce prediction errors between expected and observed actions, thereby maintaining a coherent sense of self and bodily integrity (Maselli *et al.*, 2022). The extent to which similar patterns occur in the lower limbs remains to be explored. Given the distinct functional roles and sensory characteristics of the upper and lower limbs, motor adaptations elicited through avatar control may differ when applied to the legs (Hajnal *et al.*, 2007). Unlike the upper limbs, which are optimized for dexterous tasks requiring fine motor control, the lower limbs primarily serve locomotion and stability.

To begin addressing this gap, our previous work examined how unilateral step length distortions applied to an embodied avatar affect gait symmetry, revealing that while the detection threshold for distortions influenced the SoE (Willaert *et al.*, 2024), participants did not modify their gait symmetry to align with their avatar's distorted step length (Willaert *et al.*, 2025). This lack of adaptation cannot be solely attributed to the use of the lower limbs; rather, it also reflects the specific characteristics of gait, which contrast sharply with the goal-directed and visually guided nature of the upper-limb tasks studied previously.

These previous studies have significantly advanced our understanding of when and how users adjust their movements in response to manipulations of their avatars. They show that the type of task and the available sensory cues strongly influence whether users adjust their real movements to match distortions in their avatar's actions. Nevertheless, important gaps remain in our understanding, particularly regarding how users respond to avatar distortions during goal-directed movements that are less visually guided, such as when no explicit visual target is present. In particular, lower-limb reaching movements, which are less automatic than gait, have been largely unexplored. Investigating whether and how users adapt their movements to follow their avatar when reaching without explicit visual targets, for both the upper and lower limbs, will provide new insights into the boundaries of embodiment and the mechanisms supporting motor adaptation.

To this end, the present study was designed to address the gap identified in previous research regarding how users adapt their movements to distortions of their embodied avatar during reaching tasks, without an explicit visual target.

An algorithm was developed to progressively increase the avatar's lateral deviation relative to a fixed straight-ahead reference direction, with the magnitude of distortion growing after each reach. The primary objectives of the study were to evaluate whether participants adjust their limb movements to follow the avatar's distorted trajectory during both upper- and lower-limb reaching, and to investigate how stability demands influence lower-limb reaching movements under spatial distortion. To assess the impact of stability, experimental conditions were designed to either challenge or enhance postural control. These conditions comprised performing reaching movements while balancing on a single standing leg, requiring reliance on intrinsic postural control (Yiou *et al.*, 2018), and reaching while holding onto external support to enhance stability.

We hypothesize that participants will be influenced by the avatar's distortions and align their movements more closely with the avatar's, during both upper- and lower-limb reaching tasks (H1). We further hypothesize that the impact of avatar distortions on movement execution will be more pronounced in conditions where stability is promoted through external support compared to conditions that challenge stability (H2).

6.4 Related work

6.4.1 Distorted visual feedback in virtual reality

Virtual avatars, or self-avatars, serve as digital representations of a user's body within a virtual environment, often creating the illusory experience of owning the virtual body (Sanchez-Vives *et al.*, 2010). This phenomenon, known as the SoE, arises from the integration of multisensory inputs, visual, proprioceptive, and motor, that are aligned and consistent with the user's actions. When this congruence is maintained, the brain considers the virtual avatar to be part of the user's body, leading to a sense of ownership and control over the avatar (Kilteni & Slater, 2012). Notably, the SoE has been found to be robust to certain movement discrepancies between the user's and the avatar's movements (Porssut *et al.*, 2019, 2022a). Even when distortions exceed a threshold for conscious detection, the SoE can persist if changes are introduced gradually, as observed in studies on arm-reaching tasks (Porssut *et al.*, 2019; Galvan Debarba *et al.*, 2018) and healthy gait (Willaert *et al.*, 2024).

Beyond these perceptual effects, spatial distortions applied to embodied avatars have been shown to significantly influence motor behavior. When participants observe their avatar performing distorted movements, they tend to adjust their real movements toward the avatar's altered trajectory. For instance, Burin *et al.* (2019) investigated how body ownership modulates the interaction between observed and executed movements during a continuous drawing task. Participants were instructed to continuously draw straight vertical lines within a designated zone on a virtual tablet, while their embodied avatar's hand deviated by drawing ellipses. When participants viewed the avatar from a 1PP, thus experiencing strong body ownership, their own drawing trajectories were strongly attracted toward the avatar's distorted motion, resulting in more ovalized trajectories. Moreover, this attraction effect was significantly reduced when the avatar was observed from a third-person perspective (3PP), where body ownership was diminished. The authors interpreted their results as suggesting that body ownership can alter how sensory prediction errors are processed. When participants experienced strong body ownership over the avatar, sensory discrepancies between intended and observed movements were attributed to arising from errors in their own motor output rather than from an external cause. As a result, these errors were treated as incorrect self-generated movements, leading participants to adjust their movements to the avatar's distorted trajectory in order to minimize the mismatch and preserve a coherent sense of agency and bodily self. In contrast, in the 3PP condition, where the sense of body ownership was reduced, prediction errors were more likely attributed to an external cause and thus exerted less influence on motor behavior.

Other studies have investigated how users adjust their movements when controlling an embodied avatar during goal-directed actions toward external targets. Gonzalez-Franco *et al.* (2020) and Cohn *et al.* (2020b) investigated how spatial distortions of an avatar's arm trajectory affect real-world reaching behavior. In these studies, participants performed repeated reaching movements along the anterior-posterior axis, moving straight forward from a shoulder-height starting position toward visual targets, while their avatar's arm was manipulated to deviate either laterally (up to 30° (Gonzalez-Franco *et al.*, 2020)) or vertically (up to 15° (Cohn *et al.*, 2020b)) relative to their intended straight trajectory. Participants unconsciously adjusted their real arm movements to align more closely with the avatar without being explicit instructed to do so. They suggested that these adjustments were driven by the need to minimize visuo-proprioceptive conflict arising from the mismatch between the real and virtual body position. Nevertheless, given that participants were reaching toward an explicit visual target, it is possible that some of the observed movement adjustments reflected a drive to preserve task success despite the avatar's distortion, rather than a drive to minimize visuo-proprioceptive conflict. Maselli *et al.* (2022) found that motor adjustments during goal-directed reaching are not solely driven by the intention to achieve external targets (e.g., visual target), but also by the need to minimize sensory conflicts and maintain a coherent body representation. In their study, participants performed reaching movements toward a visible target while their virtual hand was manipulated to move faster than their real hand, causing it to reach the target first. Although participants could have successfully reached the target without modifying their movement, they nonetheless adjusted their real hand velocity to align more closely with the virtual hand's accelerated trajectory, suggesting that movement adaptation was driven not only by the goal of task achievement but also by a need to minimize visuo-proprioceptive mismatch.

While embodiment-based distortions often lead to motor adaptations that preserve multisensory coherence, other paradigms reveal a different adaptation pattern where movement corrections are aimed explicitly at restoring task accuracy. In contrast to studies emphasizing multisensory coherence during avatar control, a large body of research on visuomotor adaptation has demonstrated that participants often correct their movements in the opposite direction of a visual distortion to maintain task accuracy. In these paradigms, the visual feedback of a movement is systematically altered, typically by rotating the representation of the hand's trajectory relative to its actual path. Because the rotation is applied to the ongoing movement, any adjustment made by the participant to correct their trajectory also shifts the rotated visual feedback, maintaining a persistent visuo-proprioceptive incongruence. As a result, participants cannot fully eliminate the sensory mismatch but can only adjust their movements to ensure that the virtual hand aligns with the target, reducing the error caused by the distortion and restoring task accuracy. This correction process is thought to rely on both implicit mechanisms, driven by sensory prediction errors, and explicit strategies, such as conscious re-aiming (Henriques & Cressman, 2012; Anglin *et al.*, 2017; Verhulst *et al.*, 2022).

6.4.2 Embodiment and distorted visual feedback in the lower limb

There are several key differences in motor control between the upper and lower limbs during voluntary movements. Upper limb movements are typically specialized for fine motor control, such as manipulating objects or pointing. Reaching with the lower limb requires precise coordination between movement, postural stability and trunk control. During reaching, the stance leg maintains dynamic balance through anticipatory adjustments (King & Wang, 2017; Yiou *et al.*, 2018), while the reaching leg executes coordinated movements guided by proprioceptive and visual feedback to reach a target. Despite these differences, recent studies have shown that lower-limb movements, like those of the upper limbs, are capable of adapting to altered visual feedback during goal-directed tasks. For instance, Moriyama *et al.* (2022) investigated lower-limb visuomotor adaptation using a virtual ball-kicking task presented on a large screen positioned in front of participants. In this setup, participants stood upright and swung their right foot to initiate the motion of a virtual ball displayed on the screen, while the ball's trajectory was systematically rotated by 15° clockwise or counterclockwise. Participants adapted to the altered visual feedback by adjusting their foot swing trajectory in the opposite direction of the visual distortion, effectively realigning the ball's virtual path with the intended target. This motor adaptation was accompanied by anticipatory postural adjustments in the support leg, ensuring dynamic stability and accuracy during the goal-directed task (Moriyama *et al.*, 2024). These findings indicate that, despite the fundamental differences in motor control between the upper and lower limbs, the lower limbs also exhibit adaptation to visuomotor distortions during voluntary movements.

Beyond motor adjustments, multisensory integration processes have been shown to induce a robust sense of ownership over the lower limbs in both physical and virtual environments, similar to what has been observed for the upper limbs. For example, the rubber foot illusion, induced by synchronous visual-tactile stimulation, produces a sense of ownership over the rubber foot comparable to the classic RHI (Crea *et al.*, 2015; Flögel *et al.*, 2016). Similarly, synchronous movements of the rubber and actual foot can evoke a strong sense of ownership during the moving rubber foot illusion (Teaford *et al.*, 2021). These findings extend to virtual environments, where ownership of virtual legs has been demonstrated, highlighting the role of multisensory integration in creating a sense of embodiment for the lower limbs (Pozeg *et al.*, 2015). In immersive VR, high levels of embodiment have been observed even during dynamic tasks involving the lower limbs, such as gait initiation, where participants reported a strong sense of ownership over their virtual body, even when one leg was abnormally enlarged (Vallageas *et al.*, 2024). While these findings demonstrate that the lower limbs can be successfully integrated into the bodily self through visual and sensorimotor congruence, it remains unclear how spatial distortions of embodied avatars influence motor performance during voluntary lower-limb movements, particularly during goal-directed reaching tasks. In our recent work, we applied a spatial distortion to an embodied avatar during treadmill walking by gradually increasing the avatar's step length. We found that although participants were able to consciously detect the step length distortion and experienced a progressive decrease in their sense of embodiment (Willaert *et al.*, 2024), these changes were not associated with significant alterations in gait symmetry (Willaert *et al.*, 2025). These findings suggest that healthy gait, a highly automated and rhythmic motor behavior, may be relatively resistant to visually induced spatial distortions when applied through an embodied avatar. However, it remains unknown whether voluntary lower-limb reaching, which requires more explicit motor planning and visual guidance, is similarly robust. While previous studies have shown that upper-limb reaching movements tend to adjust toward distorted avatar trajectories under similar conditions (Gonzalez-Franco *et al.*, 2020; Maselli *et al.*, 2022; Cohn *et al.*, 2020b), the extent to which lower-limb reaching adapts to spatial distortions in an embodied avatar remains largely unexplored.

The present study directly addresses this gap by investigating how spatial distortions applied to an embodied avatar influence movement adaptation during upper- and lower-limb goal-directed reaching tasks. By removing an explicit visual target, this setup creates visuomotor ambiguity, prompting participants to reconcile discrepancies between what they see (the avatar's limb position) and what they perceive through proprioceptive feedback (their actual limb position). This approach allows us to study whether participants align their movements with the avatar's distorted trajectory during reaching movements in the absence of an explicit visual target.

6.5 Methodology

6.5.1 Participants

Twenty-six participants took part in this study. Inclusion criteria required participants to have no recent upper or lower limb injuries or neurological conditions that could affect limb movements. Ethical approval was obtained from the ethics committees of CHUM (Centre Hospitalier de l'Université de Montréal) and ÉTS (École de technologie supérieure), and all participants provided written informed consent prior to the experiment. The entire experiment was completed in a single session lasting approximately two hours.

6.5.2 Materials

Throughout the entire experimental protocol, participants were asked to stand on a split-belt treadmill equipped with embedded force plates. A safety harness was used to support their weight in the event of a fall (Figure 6.1b-c). For each participant, a personalized avatar was created using MakeHuman 1.20 and was scaled according to their body height and weight. It was further customized based on gender and skin color to increase avatar resemblance. Both male and female avatars were dressed in blue shorts, a grey T-shirt, and blue trainers. A 12-camera Vicon T20-S system (Vicon Motion Systems Ltd, Oxford, UK) was used to record kinematic data at a rate of 200 Hz. Participants were fitted with 16 rigid body marker clusters attached with Velcro straps to track the movements of specific body segments: toe boxes, feet, upper legs, pelvis (at the L5-S1 level), hands, forearms, upper arms, upper spine (between the shoulder blades), and collarbones. Vicon Tracker 3.6 (Vicon Motion Systems Ltd., Oxford, UK) was used to capture real-time marker cluster data and compute the positions and orientations of body segments. Pegasus Advanced 1.2.2 retargeted the tracked segments to a virtual avatar and streamed their positions and orientations into the Unity game engine (Unity Technologies, San Francisco, CA, USA; version 2022.3.13f1) for real-time visualization within the virtual environment (VE). Motion-to-photon latency was 75 ms, measured with a 400-fps high-speed camera (Nikon 1 J4). In six trials, a user wearing motion-capture markers clapped their hands while the avatar was displayed on a monitor; latency was computed as the frame difference between the real and virtual hand contacts and averaged across the 6 trials.The VE was a virtual replica of our research laboratory, with its treadmill and safety bars replicated and co-located with their real-world counterparts. A large virtual mirror was positioned in front of participants to allow them to view their avatar (Figure 6.1a). This VE was visualized through a Meta Quest 3 (Meta Platforms, Inc., Menlo Park, CA, USA) head-mounted display (HMD) from a first-person perspective (1PP), aligned with the avatar's viewpoint.

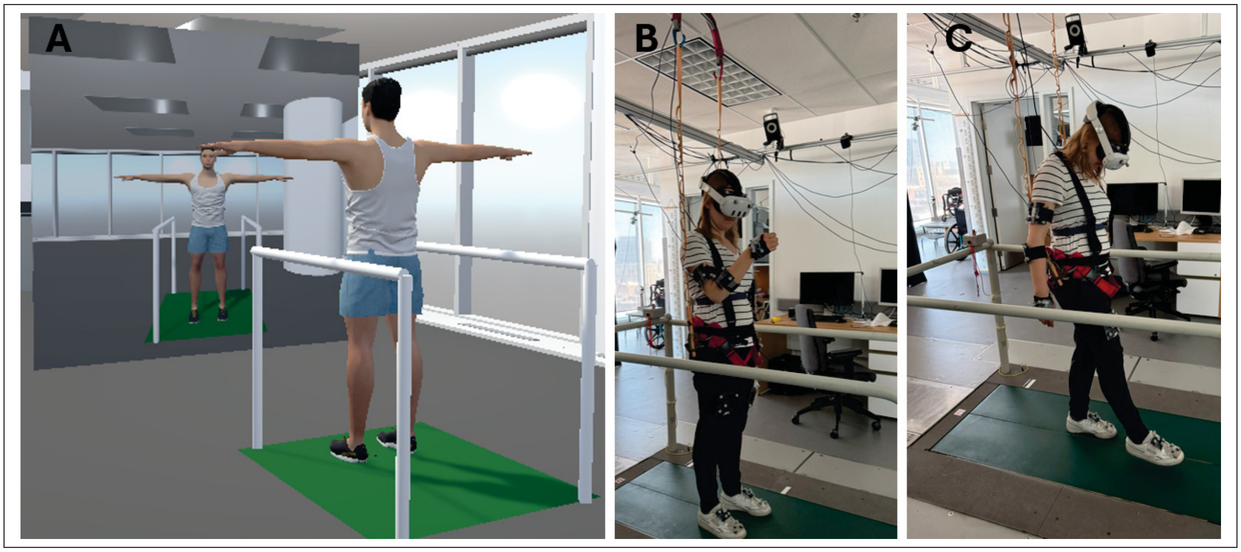

Figure 6.1 Experimental setup. (A) The VE, male avatar, virtual treadmill, and virtual mirror. (B) A participant wearing the mocap clusters and the HMD while performing the upper arm reaching task. (C) A participant performing the lower limb reaching task without holding the bars.

6.5.3 Avatar distortion

This study employed a reaching task in both upper- and lower-limb conditions, in which participants moved from a starting point, reached straight forward along the anterior-posterior (AP) axis with their hand or foot, and then returned to the starting point (Figure 6.2). To manipulate avatar movements during this task, an algorithm progressively altered the avatar's arm or leg positions over successive reaches. Specifically, the avatar's end point, initially aligned along the AP axis (straight forward), was incrementally shifted laterally after each reach, following the circumference of a circle lying in the horizontal plane. The avatar's end point was not visible to participants (details in Section 6.5.4).

6.5.3.1 Avatar arm distortion

In the upper-limb condition, a progressive lateral drift was introduced by dynamically updating the avatar's start and end points at each reach based on the participant's real-time shoulder position. Initially, both points were aligned along the AP axis, centered on the participant's shoulder joint, with the start point positioned at 40% and the end point at 80% of the participant's total arm length. Distortions were introduced by laterally displacing the end point in 1-degree increments along the circumference of a horizontal plane circle centered at the shoulder joint, with a radius corresponding to 80% of the arm length. The start point remained positioned at 40% of the arm length along the axis connecting the shoulder joint center to the distorted end point.

Each time the avatar's hand left the start point, it disappeared. Once the hand reached the end point, which remained invisible throughout the task, the start point was repositioned along the axis connecting the current position of the shoulder joint center (to account for slight postural drift during the experiment) and the next end point, which was incrementally rotated by 1 degree along the circular path. A top view of the resulting start and end points and the progressive lateral distortion can be seen in Figure 6.3. Inverse kinematics were implemented using FinalIK (RootMotion) to guide the avatar's hand toward the end point during participant reaching movements. The avatar's hand moved along a straight line between the start and end points, maintaining the same horizontal distance between the virtual shoulder and hand as between the participant's real shoulder and hand. In other words, regardless of the participant's real reaching direction, the avatar's hand advanced toward the end point with a matching movement magnitude. The same guiding of the avatar's hand trajectory was imposed for the return motion, from end point to start point. Participants were required to return their avatar's hand to the start point before initiating the next reach. Because the start point for each cycle was recalculated from the real hand position relative to the shoulder, any small misalignment between the real and virtual hand was accounted for, ensuring consistent trajectory lengths across trials. Real hand rotations were also mapped onto the avatar's hand to enhance the naturalness of movements and preserve a stronger sense of agency.

6.5.3.2 Avatar leg distortion

In the lower-limb condition, a progressive lateral drift was introduced by dynamically updating the avatar's start and end points at each reach based on the participant's real-time projected hip position. The projected hip position was defined as the point directly below the hip joint along the vertical axis, onto the horizontal plane containing the ankle joints.

Initially, the start point was placed at the height of the dominant ankle joint, under the hip joint, while the end point was positioned at 80% of the participant's lower leg length, allowing participants to reach comfortably without fully extending the leg. Both points were aligned along the AP axis relative to the projected hip position, similar to the initial alignment used in the upper-limb condition. (see Figure 6.3). Distortions were introduced by shifting the end point laterally along the surface of a circle centered at the projected hip, with a radius corresponding to 80% of the length of the lower leg.

Each time the avatar's foot left the start point, it disappeared. Once the foot reached the end point, which remained invisible throughout the task, the next end point was incrementally rotated by 1 degree along the circular path centered on the projected hip position. The start point remained fixed at the height of the dominant ankle joint, with minor adjustments based on the updated projected hip position to account for slight postural drift during the experiment.

As in the upper-limb condition, inverse kinematics guided the avatar's foot toward the end point, following a straight-line trajectory between the start and end points, while maintaining the same horizontal distance between the virtual hip and foot as between the participant's real projected hip and real foot. In other words, regardless of the participant's real reaching direction, the avatar's foot advanced toward the end point with a matching movement magnitude. The same guiding of the avatar's foot trajectory was imposed for the return to the start point. Participants were required to return their avatar's foot to the start point before initiating the next reach. Because the start point for each cycle was recalculated from the real foot position relative to the hip, any small misalignment between the real and virtual foot was accounted for, ensuring consistent trajectory lengths across trials. The Real foot rotations were mapped onto the avatar's foot to enhance the naturalness of movements and preserve a stronger sense of agency.

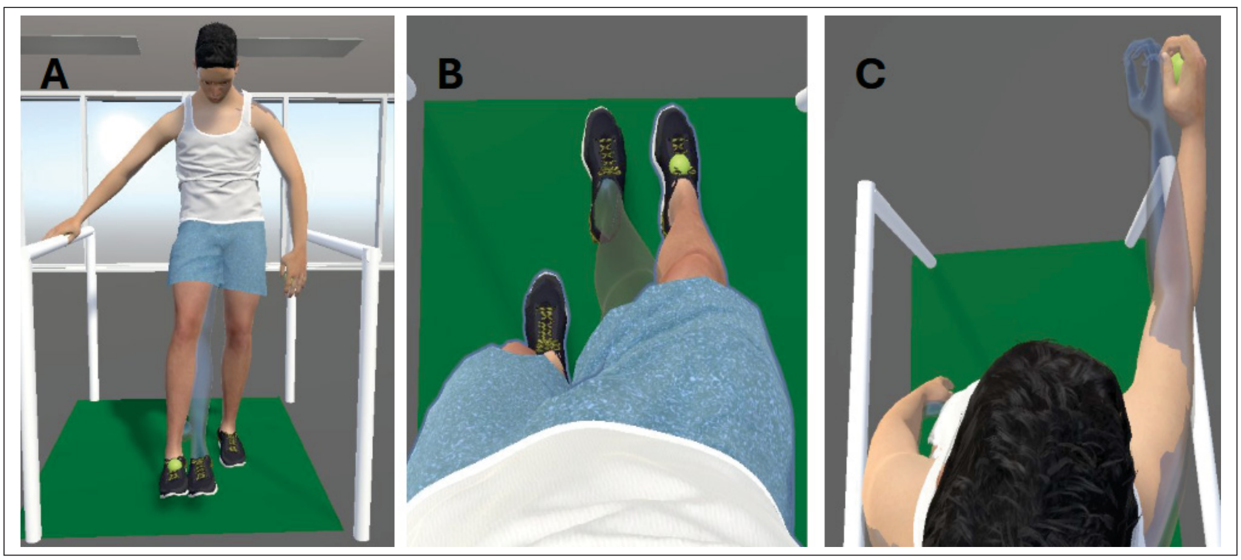

Figure 6.2 Illustration of the avatar distortion conditions. (A) Frontal view of the lower limb distortion. The translucent avatar represents the participant's actual leg position, while the opaque avatar shows the distorted position. (B) First-person perspective during the lower limb reaching task. (C) Distorted position of the arm during the upper limb task. In both conditions, only the avatar's limb was visible to the participant.

6.5.4 Experimental protocol

Hand dominance of each participant was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971), while lower limb dominance was identified by asking participants to kick a soft ball toward a wall, with the leg used for kicking considered their dominant leg. After participants were fitted with the 16 rigid body marker clusters and the HMD, they were asked to take place in the middle of the treadmill. Initially, a black screen was displayed in the HMD, and participants were asked to look straight ahead with their feet pointing straight forward and their hands resting alongside their bodies. The avatar was then calibrated by capturing the participant's real-world limb positions in this neutral stance and aligning them to the avatar's corresponding segments using Pegasus Advanced. This calibration established a reference pose from which subsequent movements were tracked and applied to the avatar in real time. Following calibration, the VE and avatar were then displayed in the HMD. To induce the sense of embodiment, participants were asked to move their upper and lower limbs for 1 minute while observing their avatar replicate their movements, either by looking down at their virtual body or by viewing themselves in the virtual mirror positioned in front of the treadmill. The virtual mirror was removed from the VE following this embodiment phase, revealing the front space of the virtual replica of the lab. This was composed of 4 meters of open space before the front wall, which had a door and counter.

The experimental phase of the study consisted of two blocks: an upper limb reaching task and a lower limb block consisting of two reaching tasks, lasting approximately 10 and 20 minutes, respectively. The blocks were presented in pseudo-randomized order across participants. Each block started with a short familiarization period of 10 reaches. The reaching tasks were only performed using the participant's dominant hand and dominant foot.

6.5.4.1 Upper body reaching task

During the familiarization period, two visual targets were positioned in front of the participant along the AP-axis, representing the start and end points of the reaching task without distortion (see Section 6.5.3.1). Participants held a tennis ball in their dominant hand, while their avatar was shown holding a virtual tennis ball in the corresponding hand. They were instructed to move the tennis ball from the starting point to the end point, and return to the starting point. After the familiarization period, the end point visual target was removed, leaving the start point was visible. The end point was visible only during the familiarization period to ensure that all participants initiated the task with a comparable forward-reaching movement. During the experimental trials, the far target was no longer shown. Instead, participants were instructed to reach forward until they heard a short auditory cue. They were told the auditory cue indicated when they had reached far enough. They were not told that the cue indicated a successful task, and received the cue for all trials across all conditions regardless of reaching direction. It is however possible that some participants could have interpreted it as a sign of success.

The upper body task consisted of two conditions. In each condition, the participant performed 20 reaches;

1. UpperLimb-NoDrift (UL ND): The avatar's arm replicated the participant's movements without any drift.
2. UpperLimb-Drift (UL D): The avatar's arm increasingly drifted laterally during each reach, resulting in a cumulative drift of 20 degrees by the final reach.

Both conditions were repeated four times, resulting in a total of eight trials. The velocity of the reaches was not controlled, but the experimenter demonstrated a target pace of approximately 1 s to reach the end point, and 1 s to return to the starting point. There was no pause between reaches, participants were instructed to initiate the next reach upon contacting the start point. Trials were presented in a pseudo-randomized order across four unique sequences, with six participants assigned to each sequence.

6.5.4.2 Lower body reaching task

In the lower-limb reaching task, participants reached forward and backward along the AP axis with their dominant leg, keeping the dominant foot approximately parallel to the floor and maintaining a consistent distance from the ground throughout the movement. The movement engaged both the hip and knee of the dominant leg, while the non-dominant leg remained firmly planted on the ground for support. During the familiarization period, two visual targets representing the start and end points of the reaching task without distortion were displayed (see Section 6.5.3.2). To ensure consistent foot alignment at the start of each trial, a virtual tennis ball was placed on top of the avatar's dominant foot. Participants were instructed to align the tennis ball with the start point before initiating each reach.

As for the upper-limb, the end point was visible only during the familiarization period to provide a consistent reference for a forward-directed reach. During the experimental trials, the far target was no longer shown. Instead, participants were instructed to reach forward until they heard a short auditory cue, indicating they had reached far enough, as for the upper limb.

The lower-limb reaching block consisted of four conditions designed to assess the influence of postural stability on motor adaptation. Reaches were performed either while holding the treadmill bar with the hand on the same side as the dominant leg (stable condition) or without holding the bar, requiring participants to balance on their non-dominant foot (unstable condition). In each condition, participants performed 20 reaches:

1. Lower Limb NoDrift Stable (LL ND Stable): The avatar's leg replicated the participant's movements without drift. Participants held the treadmill bar with their hand on the same side as their dominant leg (e.g., right foot with right hand).

2. LowerLimb Drift Stable (LL D Stable): The avatar's leg gradually drifted laterally during each reach, accumulating a total drift of 20° by the final reach, while participants held the treadmill bar with their hand on the same side as their dominant leg.
3. LowerLimb NoDrift Unstable (LL ND Unstable): The avatar's leg replicated the participant's movements without drift. Participants did not hold the treadmill bar and balanced on their non-dominant foot.
4. LowerLimb Drift Unstable (LL D Unstable): The avatar's leg gradually drifted laterally during each reach, accumulating a total drift of 20° by the final reach, while participants balanced on their non-dominant foot without holding the treadmill bar.

Each condition was repeated four times, resulting in a total of 16 trials. As with the upper-limb task, reaches were executed in succession at a pace of roughly 1 s to the end point and 1 s back, without explicit control of velocity. Trials were presented in a pseudo-randomized order across four unique sequences, with six participants assigned to each sequence.

6.5.4.3 Sense of embodiment

After completing each reaching trial in both the upper and lower limb reaching tasks, participants were asked to complete an embodiment questionnaire displayed on a large virtual screen in the VE directly in front of the treadmill. Participants kept their headsets on for this task, allowing us to assess their SoE immediately following each trial. Participants responded verbally using a 7-point Likert scale, ranging from strongly agree to strongly disagree. The questionnaire included three items adapted from a validated embodiment questionnaire established by Peck & Gonzalez-Franco (2021). A limited subset of questions was used to minimize acquisition time, given the high frequency with which the questionnaire was administered during the experiment.

1. "I felt that the virtual body was my own body."
2. "I felt like I could control the virtual body as if it were my own body."
3. "I felt as if my body was located where I saw the virtual body."

6.5.5 Data analysis

All data processing was performed using a custom-written script in MATLAB 2022a (Mathworks, Natick, USA). Statistical analyses were performed in R Studio version 2023 (RStudio, PBC, Boston, USA), with the level of statistical significance set at 0.05 for all tests.

6.5.5.1 Avatar distortions

To evaluate the impact of avatar distortions on participants' movements, angular displacement was computed for each reach by calculating the angle between the start position and the end position of the participant's movement. This angle was measured in the horizontal plane, relative to the AP-axis, representing the intended initial direction of movement. Positive angles indicated that participants followed the avatar's lateral drift, while negative angles indicated that participants moved their limb in the opposite direction (medially).

To assess the overall effects of avatar distortions, angular displacement data from all trials within each condition were aggregated across participants, and the mean angular displacement was calculated for each condition. Two separate linear mixed models (LMMs) were used to evaluate the effects of avatar distortion on angular displacement for the upper- and lower-limb tasks. Each model included Drift Type (Drift vs. No-Drift) and the avatar's distortion magnitude (20 distortion levels) as fixed effects. For the lower-limb task, Stability (Stable vs. Unstable) was included as an additional fixed effect. Random intercepts for participants were included in both models.

To examine whether inter-individual variability reflected distinct response patterns, we derived subject-level features for each condition (Upper-Limb/Drift, Lower-Limb/Drift-Stable, and Lower-Limb/Drift-Non-Stable). For each participant, we computed two features: (i) the mean signed angular displacement, and (ii) the slope from a linear model of angular displacement as a function of distortion magnitude. Features were z-scored prior to clustering. We applied k-means clustering (Euclidean distance; 50 random starts, fixed seed) separately for each condition. The number of clusters (K) selected was data-driven for each condition by maximizing mean silhouette width over K = 2–4.

To further explore the immediate effects of encountering avatar distortions, we analyzed participants' responses during their first exposure to the drift condition, when they were not yet aware that their avatar was being manipulated. We plotted the mean end angular displacements of the entire 20 reaches of the first drift condition for both the upper and lower limbs (Figure 5). We specifically looked at the mean angular displacement of the first three trials, where the distortion is presumed not to be obvious to the participants. Thus, we wanted to verify is there was a different reaction to the distortion before participants realized that the experiment involved distorting the avatar's movements. To isolate the first drift trial without prior exposure to distortion, we considered the between-subjects randomization of block order: participants began either with the upper or the lower limb block. As a result, 10 participants encountered a drift for the first time in the upper limb drift condition, and 14 for the lower limb drift condition. For the lower limb block, the stable and unstable conditions were pseudo-randomized across participants. Because there was no significant main effect of stability and no interaction between stability and other fixed effects (drift type and distortion magnitude), we computed the average angular displacement across participants' initial trials, regardless of whether they first experienced the stable or unstable drift condition, and used this mean value for group-level analysis.

6.5.5.2 Sense of embodiment

Embodiment scores were calculated by summing the responses to the three questions and dividing by the number of questions, yielding an overall embodiment score for each trial. A mean embodiment score was then computed for each condition per participant, followed by a group mean across all participants. To analyze the effects of avatar distortions on the sense of embodiment, embodiment scores from the upper-limb task were compared between conditions using the Wilcoxon signed-rank test, as normality was rejected by the Shapiro-Wilk test (W = 0.897, p = 0.020). For the lower-limb task, an LMM was employed to evaluate the effects of Drift (Drift vs. No-Drift) and Stability (Stable vs. Unstable) on embodiment scores. Post-hoc pairwise comparisons were conducted using the Tukey HSD method, which adjusts p-values for multiple comparisons. To examine whether individual differences in motor responses were associated with subjective embodiment, Pearson's correlations were calculated between embodiment scores and mean absolute angular deviations in the drift conditions (upper limb; lower limb Stable and UnStable). In addition, to determine whether the distortion effect was driven by a specific dimension of embodiment, the same analyses were repeated for each component (ownership, agency, and self-location). For the upper limb, separate Wilcoxon signed-rank tests compared Drift vs. NoDrift for each component. For the lower limb, separate linear mixed-effects models were fit for each component, with Drift and Stability as fixed effects and Subject as a random intercept.

6.6 Results

Twenty-six participants completed the study. Two participants' data were excluded due to technical issues during the experiment. The remaining twenty-four participants (12 males and 12 females; weight 74.91 kg; height 169.13 cm; age 29 years) were included in the data analysis. Nineteen participants were both right-handed and right-footed, while five participants were both left-handed and left-footed. One participant experienced a loss of balance during one reach in the lower-limb unstable drift condition (the reach with 6 degrees of drift). Consequently ,the data from that single reach was removed from further analysis.

6.6.1 Avatar distortions

Figure 6.4 illustrates the mean angular displacement during the upper and lower limb tasks. In both tasks, participants moved in the opposite direction as the avatar's distortion, indicating a medial adjustment in their movement to counter the lateral distortion (see Figure 6.3). The LMM analysis for the upper-limb task revealed no significant main effect of drift type (SE = 1.5, t(69) = -1.009, p = 0.99); however, a significant main effect of the distortion magnitude was observed (SE = 1.59, t(69) = -7.62, p = 0.001), along with a significant interaction between drift type and distortion magnitude (SE = 2.18, t(69) = 6.28, p = 0.001). Similarly, for the lower-limb task, no significant main effect of Drift Type (SE = -0.93, t(161) = -1.25, p = 0.21) was found. However, significant main effects were observed for Avatar's distortion magnitude (SE = 0.71, t(161) = -8.68, p = 0.0001), as well as for the interaction between Drift Type and Avatar's distortion magnitude (SE = 0.99, t(161) = 7.26, p = 0.0001). Stability did not have a significant main effect (SE = 0.73, t(161) = -0.142, p = 0.88), nor did it interact significantly with Drift Type and/or the avatar's Distortion magnitude.

The significant interaction observed between Drift Type and Distortion magnitude, for both the upper- and lower-limb, is expected given the structure of the task: in the No-Drift condition, participants were not subjected to any actual distortion, and thus angular displacement remained relatively stable across the distortion levels. In contrast, in the Drift condition, angular displacement varied systematically with the magnitude of the avatar's distortion. This pattern confirms that participants adjusted their movements specifically in response to the increasing distortions applied to their avatar, rather than simply over time or across trials.

To quantify the degree of counteraction, we examined the slopes derived from the LMM, which represent the change in participants' angular displacement per degree of applied distortion. A negative slope indicates that participants moved in the opposite direction to the avatar's distortion, actively attempting to counteract it. For the upper-limb task, the slope was -0.720 (p = 0.03), meaning that for every 1° of avatar distortion, participants adjusted their real arm movement by approximately 0.72° in the opposite direction. For the lower-limb task, the slope was -0.419 (p < 0.001), indicating a smaller degree of counteraction, with participants adjusting their leg movement by about 0.42° per degree of distortion. These results indicate that although participants actively counteracted the avatar distortion in both tasks, the magnitude of this counteractive movement was greater in the upper limb than in the lower limb.

In the UL D (k = 3), 8 participants were labelled over-counteractors (centroid: mean 23ř, slope 1.13), 15 were labelled counteractors (mean 8°, slope 0.53), and one was labelled a near-ignoring (mean +1.4°, slope +1.50). In the LL D Stable condition (k = 2), 8 participants were labelled as counteractors (centroid: mean 12.64°, slope 0.63), 16 as near-ignoring (centroid mean 4.7°, slope 0.360. In the LL D Unstable condition (k = 2), 14 participants were labelled counteractors (aggregate centroid mean 8.6°, slope 0.49) and 10 as near-ignoring (mean 3.5°, slope 0.18).

Figure 6.5 illustrates the mean angular displacement across participants during the initial drift trial. On average, participants deviated by -3.04° in the upper limb condition and –2.26° in the lower limb condition. The negative values from the very first reach suggest that participants began immediately counteracting the movement of the avatar.

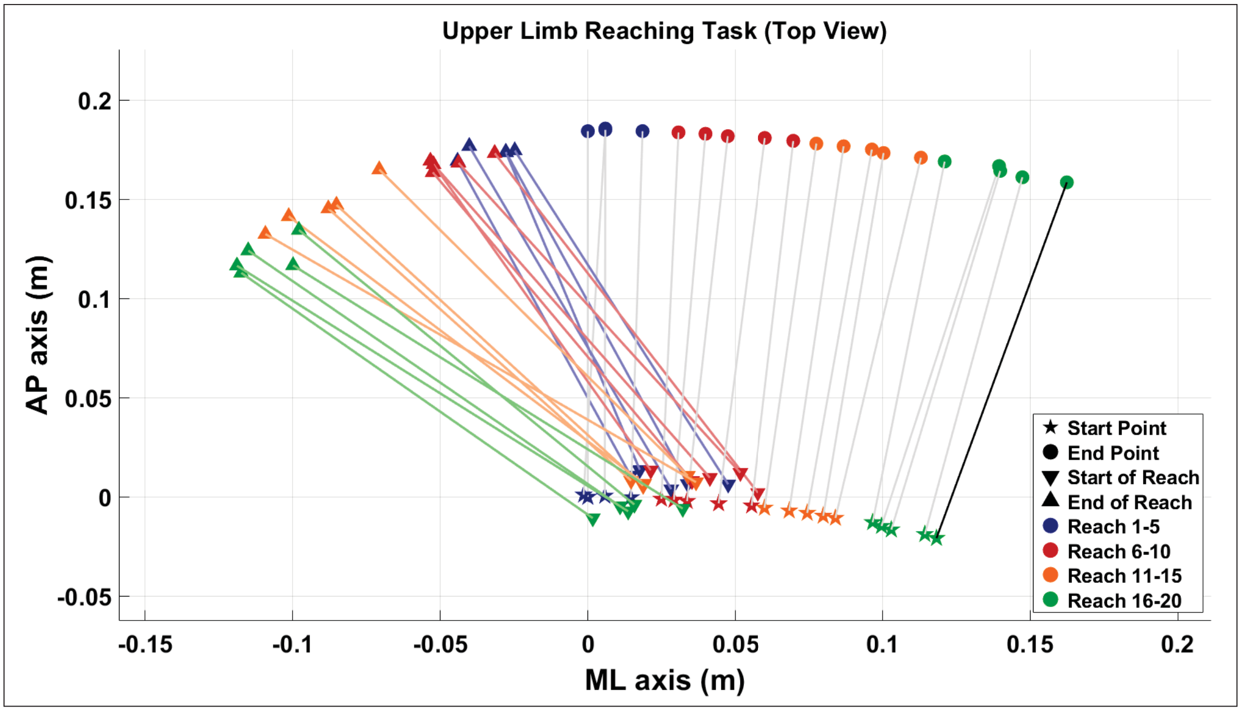

Figure 6.3 Top view of mean reaching trajectories across trials for one participant during the upper-limb reaching task. This participant was selected as a representative of the group mean pattern, illustrating progressive medial counteraction against the imposed lateral spatial drift. Trajectories are color-coded by groups of five consecutive reaches to highlight the gradual adaptation. Symbols mark key points of the movements: stars denote the true start position of each reach, circles denote the actual end positions reached by the participant, and triangles indicate the displaced end positions of the avatar under the imposed drift. The increasing medial deviation of the circles relative to the triangles illustrates the participant's counteraction to the drift. Only the upper-limb task is illustrated here, a similar counteraction was observed in both upper- and lower-limb tasks.

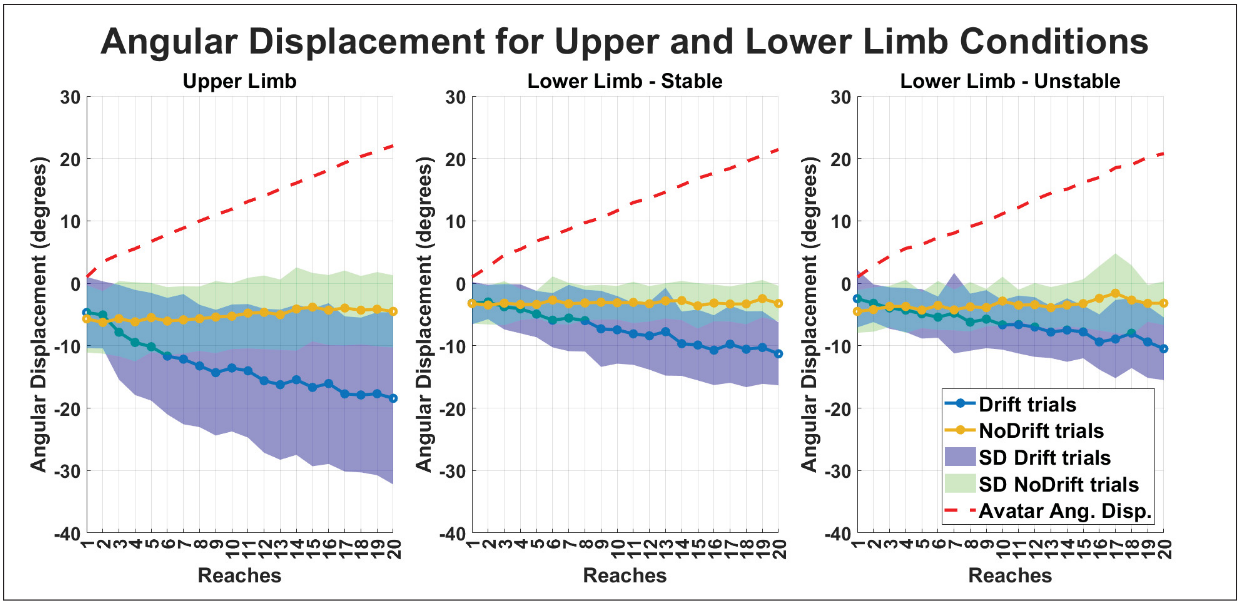

Figure 6.4 Mean angular displacement during the first Drift trial for the upper limb and lower limb tasks. The SD is indicated by the shaded region. Positive angles indicated that participants drifted laterally, following the avatar's distorted trajectory, while negative angles indicated that participants counteracted the distortion by moving medially, in the opposite direction of the avatar's limb.

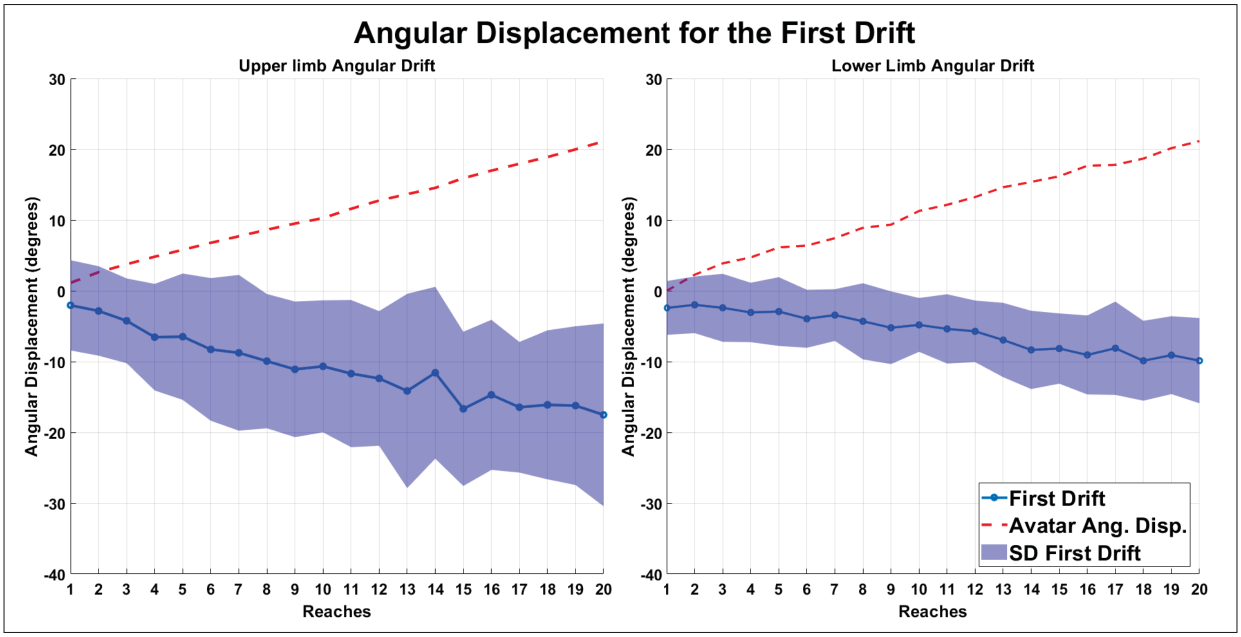

Figure 6.5 Mean angular displacement during the first Drift trial for the upper limb and lower limb tasks. The SD is indicated by the shaded region. Positive angles indicated that participants drifted laterally, following the avatar's distorted trajectory, while negative angles indicated that participants counteracted the distortion by moving medially, in the opposite direction of the avatar's limb.

6.6.2 Sense of embodiment

The mean embodiment scores are presented in Figure 6.6. For the upper limb, the Wilcoxon signed-rank test revealed that embodiment scores were significantly lower in Drift trials compared to NoDrift trials (W = 0, $p < 0.0001$). For the lower limb, the LMM showed a significant main effect of Drift (SE = 0.27, t(63) = 4.81, $p < 0.001$), indicating that spatial distortions reduced the sense of embodiment. There was no significant main effect of Stability (SE = 0.13, t(63) = 1.36, p = 0.17), and no significant interaction between Drift and Stability (SE = 0.17, t(63) = 0.87, p = 0.38). Post-hoc Tukey comparisons confirmed that embodiment scores were significantly lower in Drift compared to NoDrift conditions under both the Stable (SE = 0.27, t(63) = –5.38, $p < 0.0001$) and Unstable conditions (SE = 0.27, t(63) = –4.81, $p < 0.0001$). Correlations between embodiment ratings and mean absolute angular deviations in the drift conditions were not significant for the upper limb (r = 0.19, p = .39), the lower limb Stable condition (r = –0.08, p = .71), or the lower limb UnStable condition (r = 0.02, p = .93). To determine whether the effect was driven by a particular component of embodiment, we analyzed the three items separately. In the upper limb, Wilcoxon signed-rank tests showed significantly lower scores in Drift trials than in NoDrift trails for ownership (W = 4, $p < 0.001$), agency (W = 0, p = 0.006), and self-location (W = 0, $p < 0.001$). In the lower limb, separate linear mixed-effects models revealed a significant main effect of Drift for each component, with no main effect of Stability and no interaction; ownership (SE = 0.25, t(69) = 3.4, p = 0.009), agency (SE = 0.28, t(69) = 4.9, p = 0.001), and self-location (SE = 0.32, t(69) = 5.8, p = 0.001).

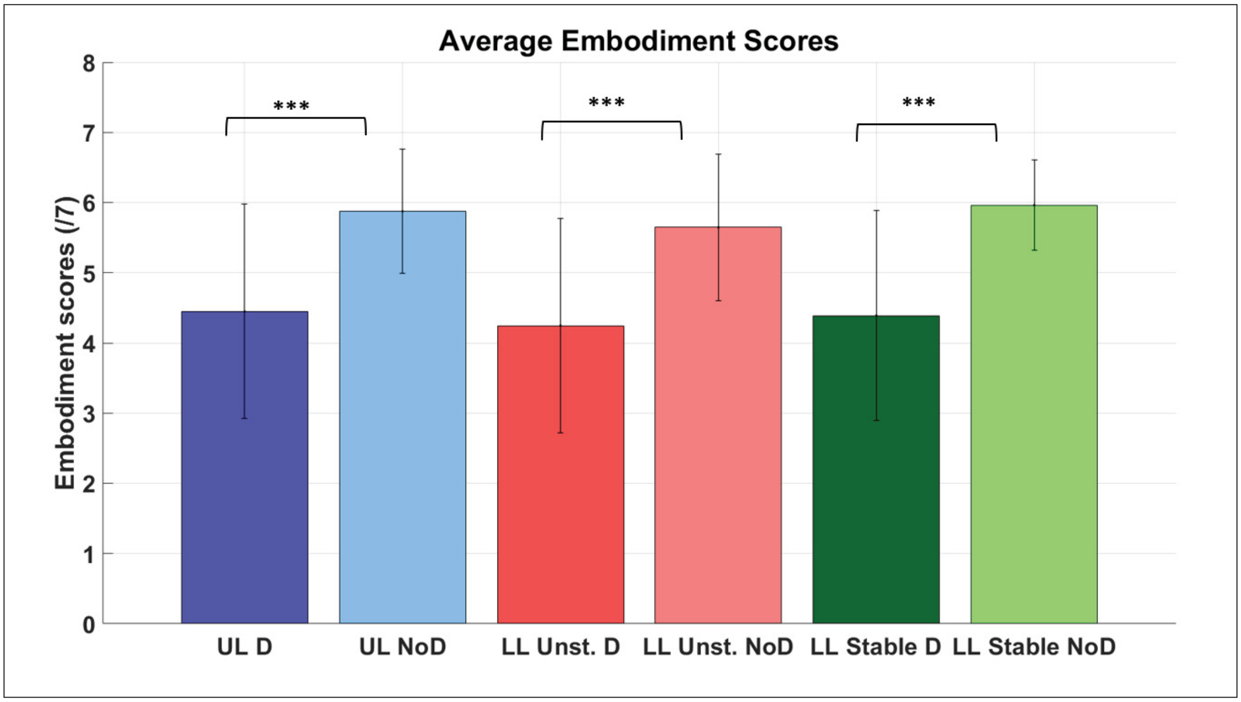

Figure 6.6 Mean embodiment scores for each condition. Error bars represent the standard deviation. The significant difference between the drift and no-drift conditions is displayed on top of the bars (Wilcoxon for UL, post-hoc Tukey HSD for LL conditions). ***$p < 0.001$

6.7 Discussion

6.7.1 Impact of the avatar distortions on reaching

The primary objective of this study was to assess whether participants would adjust their reaching movements to align with the trajectory of a spatially distorted avatar during upper- and lower-limb reaching tasks without an explicit visual target. Contrary to our initial hypothesis (H1), the results revealed that participants did not follow the avatar's distortion. Instead, they consistently adjusted their movements in the opposite direction, actively counteracting the drift.

These findings contrast with prior research on embodied avatars in immersive VR, where participants tended to align their movements with the distorted trajectories of their self-avatars, particularly during goal-directed reaching tasks involving the upper limb (Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020b). In these earlier studies, it was suggested that movement adjustments occurred to minimize visuo-proprioceptive conflict arising from the spatial mismatch between the real and virtual bodies, rooted in the multisensory integration processes that support body ownership illusions. Notably, in these studies, participants performed reaching movements toward a visible target. The distortion was applied by redirecting the avatar's hand to reach the target position, which drifted laterally on each reach, ensuring that the avatar's hand visibly contacted the target regardless of the participant's actual movement trajectory. Because the avatar consistently reached the target, participants received visual feedback indicating successful task performance, which may have encouraged them to adapt their movements to follow the avatar's distorted trajectory. Moreover, part of the observed motor adaptation could reflect participants' attempts to align their real movements towards the visual target itself, rather than a tendency to follow the avatar's movements.

In contrast, in the present study, participants corrected for the distortion rather than following it, possibly due to the absence of an explicit visual target and the lack of visual confirmation of task success. The observed distinction between the present findings and prior work can be further explained using the framework proposed by Maselli *et al.* (2022), which suggests that movement adaptation can be driven either by intentional control (goal-directed corrections to achieve a desired outcome by compensating for sensory discrepancies), by conflict-resolution mechanisms (adjustments made to reduce multisensory conflict), or by a combination of both. When a mismatch occurs between the predicted and actual movement outcome, participants may rely on intentional control to adjust their movements and successfully reach the target. In doing so, they effectively reduce both the motor error and the associated sensory discrepancy. Because the sensory conflict is resolved through goal-directed correction, there is no need for additional conflict-resolution mechanisms to align the perceived and actual body states.

In previous studies where the avatar's hand was consistently redirected to reach a visible target (Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020b), participants still completed the task successfully despite experiencing a sensory mismatch. In these cases, adjustment was more likely driven by conflict-resolution mechanisms aimed at minimizing multisensory discrepancies. In such embodied scenarios, participants did not interpret the avatar's misalignment as an error requiring motor correction; instead, they gradually shifted their real limb toward the avatar's trajectory to reduce the ongoing sensory conflict (Cohn *et al.*, 2020b; Gonzalez-Franco *et al.*, 2020; Maselli *et al.*, 2022).

In contrast, in the present study, no visual target was provided. Participants were instructed to continue reaching forward, possibly guided by a memory of the target location acquired during the familiarization phase, when the end point had been visible. The distortion would then have affected the desired straight, forward trajectory, leading participants to perceive it as an execution error requiring active correction. Although the trajectory of the avatar was always directed towards the distorted end point no matter the direction of the participant's reach, meaning they could have aligned with their avatar, they consistently corrected in the opposite direction. This indicates that the intentional control imperative, as described by Maselli *et al.* (2022), took precedence. Participants prioritized achieving the expected movement outcome rather than minimizing the visuo-proprioceptive mismatch by aligning with the avatar.

Compensatory responses are commonly observed in visuomotor adaptation studies, where participants initially adjust their movements in the opposite direction of a distortion to maintain accuracy when visual feedback is rotated (Mazzoni & Krakauer, 2006; Modchalingam *et al.*, 2023). Similarly, the present findings suggest that participants actively monitored the distortion and applied corrective adjustments rather than aligning their movements with altered feedback. However, unlike visuomotor adaptation studies, which typically involve an explicit target allowing participants to correct spatial discrepancies between their limb and the goal, the current study lacked such a reference point. Despite this absence of external error feedback, participants still treated the misalignment as an execution error and corrected their movements to restore consistency between their expected and actual limb positions. Furthermore, there was no tendency to follow the avatar's distorted trajectory, even during the initial exposure to the drift trials at the lowest distortion levels (Figure 6.5). This suggests that participants did not gradually adapt to a perceived mismatch, but instead immediately treated the distortion as an execution error to be corrected.

Moreover, participants persisted in correcting their movements in the opposite direction of the distortion, even though this had no observable effect on the avatar's trajectory and no external feedback indicated whether their corrections were effective. These findings align with the active inference framework, which proposes that actions are generated to minimize internal prediction errors, discrepancies between expected and actual sensory input rather than to maximize external rewards or outcomes (Friston, 2010). Under active inference, such corrections can be understood as attempts to fulfill strong prior expectations about how movements should feel and unfold, for example, the expectation that the limb should move in a straight line. When the avatar's limb drifted laterally, this violated participants' predicted visual feedback. Participants continued to counteract the distortion in ways that reduced the mismatch between their intended movement and the sensory consequences they experienced, even though these corrections had no impact on the avatar's visual trajectory or task success. They were not reacting to external feedback, but were instead attempting to minimize internal sensory prediction errors based on their prior expectations about how a forward reach should feel and unfold.

Our findings are consistent with previous research showing that internal representations of target locations can support accurate movement planning in the absence of continuous visual feedback. For example, Berret *et al.*

(2014) demonstrated that participants could execute accurate pointing movements based on remembered visual targets, relying on proprioception and internal models after the target disappeared. This suggests that in our task, participants may have formed stable visuomotor plans during the familiarization phase and relied on them to detect and correct discrepancies introduced by the avatar's distortion.

The degree of counteraction scaled with the imposed distortion; the larger the deviation in the avatar's trajectory, the greater the compensatory movement in the opposite direction for both the upper and lower limb tasks. In the upper limb task, a clear trend emerged, where larger distortions led to near proportionally stronger counteracting movements. This suggests that participants were continuously tracking the mismatch between their expected sensory feedback (e.g., a straight forward reach) and the distorted visual input. Being embodied in a full-body avatar may have amplified this effect: despite the spatial distortion, participants continuously received visuomotor feedback from a first-person perspective that was synchronized with their own movements. This real-time sensorimotor coupling likely enhanced the integration of visual and proprioceptive signals, reinforcing the sense of ownership over the avatar's body (Maselli & Slater, 2013; Maselli *et al.*, 2015). Such multisensory integration could have increased proprioceptive awareness, enabling participants to detect subtle discrepancies between expected and observed movement outcomes and to apply corrections proportionally matched to the imposed distortion. In the lower-limb task, this pattern was less pronounced. Although counteraction was still correlated with the level of distortion, the adjustments were not as precisely scaled as in the upper-limb task. Several factors may explain this difference. First, the distortion between the intended and visually represented position of the foot may have been less accurately perceived due to the lower spatial localization acuity of the feet compared to the hands (Darling & Yem, 2023). Second, generating medial movements that cross the body's midline is more constrained in the lower limbs, given their stronger coupling with postural control demands. In contrast, upper limbs are optimized for midline crossing and for executing precise, goal-directed actions (Baldissera & Tesio, 2017). As such, corrective adjustments in the lower-limb task may have been more biomechanically demanding.

Participants performed both tasks while standing, unlike previous studies that used seated conditions during goal-directed movements of the upper limb (Cohn *et al.*, 2020b; Gonzalez-Franco *et al.*, 2020; Maselli *et al.*, 2022). Performing goal-directed movements while standing increases postural control demands, requiring whole-body coordination to maintain balance throughout the movement to maintain balance and prevent falls (Dierijck *et al.*, 2020; Leonard *et al.*, 2009). This increased postural engagement may have led to greater reliance on proprioceptive feedback, enhancing participants' perception of their actual movement trajectory relative to the avatar. For the lower limb task, postural demands were likely even higher, as it required greater whole-body coordination, where the standing leg provided stability while the reaching leg executed the movement (King & Wang, 2017; Yiou *et al.*, 2018). This demand was particularly pronounced when participants were not holding onto the treadmill bars, requiring them to balance on one foot while reaching. However, the results showed no significant difference between the two conditions (LL Drift Stable and LL Drift Unstable), indicating that the increased stability provided by holding the treadmill bars did not influence the fact that participants counteracted the distortion. As a result, the second hypothesis (H2), which proposed that the impact of avatar distortions on lower limb reaching movements would result in greater alignment with the avatar in conditions where stability was promoted, was not supported. These findings suggest that, similar to the upper limb condition, participants interpreted the distortion as an error that needed to be corrected, actively adjusting their movements to align the avatar's leg trajectory with their intended movement, even under increased stability demands.

Taken together, the findings of this study contribute to the ongoing research on how embodied avatars affect motor performance by demonstrating that spatial mismatches between a user's actual movements and those of their self-avatar can significantly alter motor behavior. Participant's responses to these mismatches appear to depend on specific task features. In previous studies, during goal-directed movements participants tended to follow the avatar's distorted trajectory when a visual goal was present and the distortion did not prevent the avatar from successfully reaching the target. Under such conditions, participants can resolve the visuo-proprioceptive conflict by gradually aligning their actual movements with the avatar's trajectory, preserving task success while minimizing sensory mismatch (Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020b; Maselli *et al.*, 2022). Our study demonstrates that removing the visual targets leads to the embodied participant trying to correct the distorted movement of its avatar, rather than following it. Our experiment led users to interpret the mismatch as an execution error and prioritize internal movement goals over minimizing sensory conflict. Notably, although the experimental setup allowed participants to reduce the mismatch by aligning with the avatar, they instead corrected in the opposite direction. This suggests that the tendency to follow the avatar's trajectory is not solely determined by the presence of a distortion, the capacity to reduce it, or the level of embodiment, but also by whether the distortion supports or interferes with task success during goal-directed reaches of the upper and lower limb.

6.7.2 The sense of embodiment

The embodiment analysis revealed that drift conditions significantly reduced embodiment compared to conditions when no distortions were applied. Importantly, these effects were consistent across both arm and leg reaching movements. Similar findings have been reported in studies of upper body reaching tasks, where introducing a spatial drift led to a significant decrease in embodiment (Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020b). Consistent with these studies, the results of this study similarly reported that while embodiment was diminished during drift conditions, it was not entirely disrupted, as some degree of embodiment was still maintained. The avatar's distorted movements were spatially offset but remained synchronized with participants' actual movements. This visuomotor synchronization likely played a role in preserving a sense of agency and ownership over the avatar, as previous research has demonstrated that this synchronization is a key factor in maintaining the illusion (Kokkinara & Slater, 2014).

6.7.3 Limitations

This study did not directly assess at which point participants became conscious aware of the distortion or whether they were aware of their counteractive movements. As a result, it remains unclear whether the compensatory responses were entirely implicit or partially guided by explicit recognition of the spatial offset and a conscious effort to correct the avatar's movement. Another limitation is that embodiment was only assessed after each series of reaches and not during the distorted movements themselves. Since the embodiment questionnaire was administered after each trial, during which distortion levels gradually increased up to 20%, participants' responses may have been more influenced by the latter, larger distortion during the task. Previous research has shown that retrospective subjective evaluations are often weighted toward the most recent experiences or end states of an event (Fredrickson & Kahneman, 1993).

6.7.4 Potential applications in motor rehabilitation

The findings of this study could have implications for motor rehabilitation, particularly in the design of avatar distortions for therapeutic use. The behavior observed in this study, where participants made compensatory movements in response to a distorted avatar trajectory, resembles patterns seen in error augmentation paradigms. In such paradigms, movement errors are intentionally amplified, typically through manipulated visual or physical feedback, to encourage corrective responses and promote motor adaptation (Patton *et al.*, 2013; Abdollahi *et al.*, 2014). However, such approaches usually involve an explicit performance goal and provide success or failure feedback to guide learning. In contrast, participants in our study received no external feedback and were not given an explicit target, yet they consistently made corrective adjustments. This approach could potentially be used in rehabilitation setting, particularly for stroke patients who often experience proprioceptive deficits and impaired movement accuracy in the affected limb during goal-directed reaching (Jones, 2017). By introducing subtle mismatches between the avatar's movement and the patient's actual movement, it may be possible to elicit corrective behavior, without requiring external reinforcement or explicit instruction.

However, these findings were obtained from healthy participants with no upper or lower limb impairments and may not fully translate to stroke patients. Although stroke survivors have demonstrated the ability to perceive and adapt to visual distortions in motor tasks (Moore *et al.*, 2024), the mechanisms underlying these adaptations may differ when using embodied avatar-based distortion protocols. Nonetheless, immersive VR studies have shown that stroke patients can still experience comparable levels of proprioceptive drift and embodiment to healthy individuals, although the sense of embodiment may be less vivid (Borrego *et al.*, 2019; Llorens *et al.*, 2017). Future research should explore whether stroke patients exhibit responses similar to healthy participants when exposed to visual distortions during reaching tasks involving the upper and lower limbs with embodied avatars.

6.8 Conclusion

The results of this study revealed that spatial offsets applied to an embodied self-avatar significantly affected participants' motor responses. Contrary to previous research suggesting that users tend to follow distorted avatar trajectories to minimize sensory conflict, our findings demonstrate that individuals actively counteracted the distortion by moving in the opposite direction. This corrective behavior occurred consistently across both upper- and lower-limb reaching tasks, in the absence of external feedback or visual targets, potentially reinforcing the perception of the distortion as an execution error rather than a sensory conflict to be resolved. These findings contribute to a better understanding of how embodied distorted avatars influence motor performance in goal-directed movements, with potential applications for rehabilitation strategies aiming to stimulate voluntary motor corrections. Future research should explore whether similar correction patterns and underlying mechanisms can be elicited in clinical populations, such as stroke survivors.

CHAPTER 7

GENERAL DISCUSSION

7.1 Main findings

The main objective of this thesis was to investigate whether healthy individuals adjust their movements in response to spatially misaligned embodied avatars in immersive virtual reality. Specifically, we examined whether such motor adjustments occur during both gait and goal-directed reaching tasks involving the upper and lower limbs, when no visible target is present. We further explored how the sense of embodiment relates to these adjustments. To address this objective, three experimental studies were conducted.

Article 1 investigated participants' ability to detect spatial distortions during treadmill walking, in which the step length of the embodied avatar was either progressively increased or decreased. We found that participants failed to detect step length distortions up to thresholds of approximately 12% and 9% in the ascending and descending conditions, respectively. Embodiment decreased as distortion increased, yet detection alone did not break the sense of embodiment, nor was there a rapid decline seen after detection. Participants continued to report feeling embodied in their avatars even when aware of the mismatch. These findings led us to reject our first hypothesis (H1), which proposed that the detection of the step length distortion would lead to a break in embodiment.

Furthermore, our results show that high levels of embodiment can be re-established by gradually reducing an initially large distortion, rather than relying on the conventional approach of gradually introducing distortion after establishing embodiment (Maselli & Slater, 2013). This supports our second hypothesis (H2), which proposed that the sense of embodiment would remain consistent at a given distortion level, regardless of whether the distortion was increasing or decreasing.

In Article 2, we sought to examine whether the changes in embodiment observed under step-length distortion and the conscious detection of these distortions would translate into measurable gait modifications during treadmill gait. We applied spatial distortion to one of the step lengths of a full-body embodied avatar to create gait asymmetry. However, participants maintained stable gait symmetry across all distortion levels, despite perceiving the mismatch. This outcome contradicted both Hypotheses 3 and 4 (H3, H4), which predicted that participants would adjust their own step length to follow the avatar's, and these would persist after detecting the distortion. These findings suggest that gait, as an automatic motor behavior, is relatively resistant to visuo-proprioceptive discrepancies introduced through avatar-based feedback, even when these distortions affect the sense of embodiment.

Article 3 examined whether participants would align their movements with those of the avatars in the absence of a visual target. However, contrary to our fifth hypothesis (H5), participants did not follow the avatar's distorted leg trajectory. Instead, they consistently counteracted the distortion by moving in the opposite direction. Moreover, this pattern was also observed in the upper-limb condition, suggesting that under identical conditions, similar resistance to the distortion emerged across limbs.

A comparable response was observed during the more demanding lower-limb condition, where participants performed reaching movements while balancing on one foot without external support. Regardless of whether participants held onto the bars or not, they consistently reached medially to counteract the avatar's lateral drift. These results led us to reject our sixth hypothesis (H6), suggesting that stability constraints did not significantly influence correction behavior.

While previous studies have reported that participants tend to follow the trajectory of a distorted avatar, especially during goal-directed movements involving the upper limb with visible targets (Gonzalez-Franco *et al.*, 2020; Cohn *et al.*, 2020a; Maselli *et al.*, 2022), our findings suggest that this behavior may depend on the presence of visual targets, rather than being a consistent outcome of embodiment alone.

In those earlier studies during goal-directed movements, the distortion did not prevent the avatar's limb from reaching the visual target. Consequently, participants were able to maintain task success (i.e., reaching the target) by gradually adjusting their own limb movements to align with the distorted avatar. This observed change in movement execution was interpreted as a reduction in visuo-proprioceptive mismatch (between the avatar's visual trajectory and the participant's actual limb position), without compromising the ability to complete the task.

In contrast, in our studies, both in gait (Article 2) and goal-directed reaching (Article 3), no visual target was presented, and participants showed no tendency to follow their avatars. In the gait study (Article 2), participants did not adjust their gait to follow the avatar's distorted step length. Instead, they maintained symmetrical gait patterns, and their lower-limb kinematics remained stable across all distortion levels. This aligns with the view of gait as a highly patterned and robust motor behavior, governed primarily by the dynamics of balance and propulsion (Winter, 1995). Although the avatar's step length was distorted, the manipulation preserved visuomotor synchrony: the avatar's movements still corresponded to the participant's real-time body movements. Only the step length was spatially exaggerated, while posture, balance, and forward progression remained unaffected. From both the first-person perspective and the virtual mirror, the avatar's appearance remained coherent and stable. As a result, even when participants consciously perceived the step length distortion, it did not interfere with their own movement and was likely treated as irrelevant to task success. This may have led to the distortion being downweighted during motor control, allowing participants to maintain symmetrical gait patterns despite the mismatch. Moreover, participants were walking on a treadmill, which acted as a constant physical and visual reference for step timing and foot placement. This likely reinforced consistent gait patterns and contributed to the automatic regulation of locomotion, even in the presence of a distorted visual step length.

In the reaching task (Article 3), participants performed repeated forward movements without a visual target, while the avatar's trajectory progressively deviated laterally with each reach from the initial straight-ahead direction. Participants consistently corrected in the opposite direction of the distortion, suggesting that they perceived the avatar's lateral deviation as an execution error that needed to be corrected to maintain their intended movement trajectory. One theoretical account for this behavior is offered by the active inference framework (Friston, 2010; Maselli *et al.*, 2022), which proposes that actions are generated to minimize prediction errors, discrepancies between the expected sensory consequences of movement (e.g., a straight-ahead reach) and the actual sensory feedback (e.g., the avatar's lateral deviation). In this view, movements are guided by prior expectations about the sensory consequences of one's actions. In our study, the progressively deviating avatar created a mismatch between the expected straight-ahead reach and the visual feedback. This violation of expectation likely led participants to adjust their movements in the opposite direction to restore consistency between predicted and actual sensory input.

Together, these findings suggest that the tendency to follow the avatar's trajectory in immersive VR depends not only by the presence of a distortion, the capacity to act upon to reduce the mismatch or the level of embodiment but by how the distorted movement interacts with the participant's movement goals and the demands of the task. In the gait task, the visual discrepancy may have been downweighted because it did not interfere with walking or hinder task performance. Since the distortion had no impact on gait symmetry or goal achievement, participant likely relied on proprioceptive feedback, such as limb position sense, foot contact with the treadmill, and mechanisms supporting upright postural control, to maintain their natural gait pattern despite the avatar's mismatched step length. In contrast, during goal-directed reaching, when a visible target is presented in the scene an the avatar's distorted movement continues to successfully reaches the target, participants may adjust their movements and follow the distorted trajectory. However, in the absence of a visual target, as in our study, the distortion conflicted with participants' intended straight forward movement. This conflict may have led participants to produce corrections that opposed the avatar's distortion, reflecting an attempt to maintain a consistent forward movement direction rather than to align with the avatar's altered motion.

These findings contribute to our understanding of how distorted embodied avatars affect motor behavior. They underscore that high embodiment and visuomotor congruence alone are not sufficient to induce alignment with the avatar's movements. Instead, alignment tends to occur when the distortion remains compatible with the participant's movement goal and does not interfere with successful task performance. Depending on whether the distortion facilitates, disrupts, or is irrelevant to the intended movement, participants may follow it, correct against it, or disregard it.

7.2 Future research directions and potential applications in motor rehabilitation

The findings of this thesis raise several important questions that future studies could address to deepen our understanding of how individuals respond to spatial distortions in embodied avatars in the absence of visual targets.

While our findings obtained from the gait study (Articles 1 and 2) provide new insight into how healthy individuals respond to avatar-based distortions, the relationship between distortion detection, the sense of embodiment, and resulting motor behavior remains incompletely understood, particularly in the context of gait. Although participants were able to detect step length distortions, they did not modify their gait symmetry, making it difficult to assess whether conscious awareness of the distortion or embodiment had any influence on their motor behaviour.

In contrast, in Article 3, we observed consistent corrective responses during goal-directed upper and lower limb reaching without visual targets, whereas previous research has shown that participants tend to follow the avatar's distorted trajectory when a visible target is present (Cohn *et al.*, 2020a; Gonzalez-Franco *et al.*, 2020; Maselli *et al.*, 2022). What remains unclear is how the conscious awareness of a distortion and the sense of embodiment modulate these behavioral responses.

Future studies should estimate distortion detection thresholds during reaching tasks by gradually increasing the distortion across trials and asking participants to indicate the moment they become explicitly aware of the mismatch. To assess how the sense of embodiment evolves throughout the task, the embodiment questionnaire can be employed at predefined time points, such as before the task, midway through, and after completion. This approach would help clarify whether the magnitude or persistence of corrective responses changes once the distortion becomes consciously detectable, and how changes in embodiment relate to these motor adjustments. Moreover, it could shed light on whether the counteraction is initiated implicitly or whether it becomes a conscious adjustment once the distortion is noticed.

Similar detection and embodiment assessments could be applied to protocols involving visible targets, where participants have been shown to follow the distorted avatar. This would help determine whether the following behaviour reflects a lack of awareness of the distortion or a conscious strategy to prioritize task success despite visuo-proprioceptive conflict.

Furthermore, in Article 3, the distortion was applied such that it progressively increased a lateral deviation in the avatar's trajectory relative to a fixed straight-ahead reference direction, thereby creating an increasing misalignment between the avatar's and the participant's intended reach path. However, it remains unclear how participants would respond if the distortion were applied along their intended reach direction, altering the movement amplitude rather than its direction.

Future studies could address this by implementing a distortion aligned with the participant's intended reach vector, as introduced in Maselli *et al.* (2022), but without the presence of a visual target. In such a design, participants would perform the reaching task in response to an auditory cue, while the avatar's trajectory is gradually displaced along the reach direction, so that the avatar's reach amplitude exceeds that of the real limb, without any external visual goal. This would allow researchers to assess whether participants counteract the distortion by reducing their own reach amplitude, or begin to align with the avatar's exaggerated movement a a response to the visuo-proprioceptive conflict.

It is important to note that the gait-related findings reported in this thesis were obtained from healthy participants whose walking patterns are inherently symmetrical and optimized for balance and efficiency. In this population, we identified a detection threshold (Article 1) for gait distortions in a self-avatar with unilaterally increased step length, and found no significant changes in gait symmetry in response to the distortion (Article 2), suggesting that the automaticity of healthy gait may limit responsiveness to such visual manipulations.

Nonetheless, these findings may have potential implications for motor rehabilitation, particularly in the context of designing avatars for therapeutic use. They provide a better understanding of the size distortions that can be applied to an embodied avatar's gait while remaining below a predefined detection threshold, without disrupting the sense of embodiment. If embodiment decreases, the distortion can be scaled down accordingly, allowing the avatar's altered movement to still be perceived as part of the self. This approach could help patients perceive corrected movement patterns as their own, potentially enhancing rehabilitation outcomes (Tambone *et al.*, 2021).

That said, these findings may not translate directly to clinical populations. For example, individuals recovering from stroke often exhibit step length asymmetry Patterson *et al.* (2008) and, depending on the lesion location, have proprioceptive deficits and tend to rely more on visual feedback Bernard-Espina *et al.* (2021); Bonan *et al.* (2004). In such cases, both the detection thresholds for step length distortion and the motor responses to avatar-based gait manipulation may therefore differ in patients suffering from motor and sensory deficits.

Moreover, the therapeutic objectives in rehabilitation differ from the aims of our experimental studies. In our research with healthy participants, the goal was to determine whether the step length distortion could disrupt naturally symmetrical gait patterns. In contrast, stroke rehabilitation aims to reduce pre-existing step length asymmetry and promote symmetrical gait. In this context, self-avatar distortions could be used to visually exaggerate the shorter step or reduce the longer step, thereby guiding patients toward more symmetrical walking. However, the effectiveness of such an approach would depend on how patients perceive these visual distortions and how this influences their motor behavior.

Given that healthy participants did not modify their gait in response to the distortion, neither by following the avatar's longer step nor by compensating with the opposite limb, it remains unclear whether stroke patients would show similar resistance or instead begin to align with or correct for the distortion. Understanding whether patients tend to align with or resist these visual distortions is essential for designing effective interventions. Thus, future studies are needed to examine how the detection threshold, motor adaptation, and the sense of embodiment interact in neurologically impaired populations during gait. Such insights could help guide the development of embodied avatar–based rehabilitation protocols tailored to the unique needs of patients with neurological impairments to promote functional gait improvements.

The results from Article 3 also involved healthy participants and demonstrated that they corrected their real movements medially in the opposite direction of the lateral introduced avatar distortion during the upper and lower limb reaching tasks without visual targets. While this suggests a compensatory response, it remains unclear whether participants would also correct in the opposite direction (i.e., laterally) if the distortion were applied medially, as this condition was not tested. Future research could investigate if similar response are observed when the avatar is distorted medially.

Reaching movements typically involve the active movement of a specific limb (e.g., arm or leg) that execute the motion, supported by a postural chain that stabilizes the body during the action. When the avatar's motion was distorted, this may have disrupted the expected relationship between the moving limb and postural segments, leading participants to correct their movement to maintain overall body stability. Future studies could incorporate measures of center of pressure (CoP) and center of mass (CoM) to assess whether and how participants engage their postural system when correcting for the avatar's distortions.

From a rehabilitation perspective, understanding whether and how individuals engage both limb correction and postural control in response to distorted visual feedback may offer valuable insights for motor recovery strategies. Stroke patients often experience impairments in both voluntary movement execution and postural stability, and tasks that engage the coordination between these systems could be particularly relevant for stroke patients where restoring the ability to adjust movement while maintaining balance is critical for functional recovery. If visual distortions to a self-avatar can elicit comparable responses in stroke survivors, such paradigms could provide a promising framework for exploring how individuals with motor impairments adapt to avatar distortion and whether this process might support the retraining of movement-posture coordination and the role of the sense of embodiment. Future research should explore whether patients show similar compensatory patterns and whether task parameters (e.g., distortion direction, limb used, or balance demands) can be tailored to target specific motor deficits.

CONCLUSION

This thesis set out to investigate how healthy participants respond to spatial distortions applied to an embodied avatar during both gait and goal-directed reaching tasks involving the upper and lower limbs in immersive virtual reality. Across three experimental studies, we examined whether individuals would adjust their real-world movements to align with the distorted avatar's trajectory and how the sense of embodiment modulated these responses.

This thesis demonstrates that spatial distortions applied to an embodied avatar affect motor behavior differently depending on whether they occur during gait or during goal-directed reaching movements and the structure of the task.

During gait, participants could tolerate a certain level of spatial mismatch between their own body and the avatar without consciously detecting the distortion. This tolerance allowed the sense of embodiment to persist even in the presence of noticeable visuomotor conflicts, suggesting that embodiment can be resilient to spatial distortions, as long as they remain within perceptual thresholds. Notably, this thesis also introduces a novel perspective on how embodiment can be restored. Whereas previous work has typically induced embodiment by starting from visuomotor congruence and after it has been broken by spatial distortion, our results show that reducing a large, initially detectable distortion can also reestablish high levels of embodiment.

Yet, this tolerance for distortion did not lead to motor adaptation during gait. Despite maintaining a strong sense of embodiment, participants did not adjust their walking patterns to align with the avatar's distorted movements. This highlights that while the avatar's body may be perceptually accepted as one's own, even when spatially distorted up to a threshold, this is not sufficient to alter well-practiced motor behaviors like locomotion, particularly in the absence of task-relevant goals.

In contrast, during the goal-directed reaching task, participants were embodied into a full-body avatar but did not align their movements with the avatar. Instead, they actively counteracted the distortion. This finding underscores the importance of task structure: in the absence of a visual target to guide movement, participants prioritized internally generated motor goals and proprioceptive feedback over the avatar's visual motion.

Together, these findings offer new insights into the boundaries of embodiment and the mechanisms supporting motor adaptation in immersive virtual environments. It shows that a strong sense of embodiment does not necessarily lead to behavioural motor alignment with the avatar. Instead, our results suggest that motor adaptation to avatar distortions is shaped by the presence of an explicit task goal. When these distortions conflicted with, or were irrelevant to, the intended movements, participants either counteracted them during reaching tasks, even when doing so had no impact on task success, or disregarded them entirely in the context of gait.

These insights may inform future research on the interaction between distorted visual feedback, the sense of embodiment, and motor performance. By providing a better understanding of the conditions under which users counteract or align with distorted movements, this work can also inform the design of VR-based motor rehabilitation protocols that incorporate altered real-time visual feedback delivered via an embodied avatar, with the aim of improving functional outcomes.

APPENDIX I

TABLES IN ANNEXES

Distortion(%)	Subject 1			Subject 2			Subject 3		
	SL	**Av. SL**	**SD**	**SL**	**Av. SL**	**SD**	**SL**	**Av. SL**	**SD**
1	0.633	0.640	0.003	0.575	0.564	0.008	0.553	0.561	0.005
2	0.640	0.648	0.004	0.580	0.565	0.011	0.559	0.562	0.002
3	0.646	0.659	0.007	0.586	0.574	0.009	0.564	0.569	0.003
4	0.652	0.659	0.003	0.592	0.584	0.005	0.570	0.573	0.002
5	0.658	0.658	0.000	0.597	0.596	0.001	0.575	0.580	0.003
6	0.665	0.673	0.004	0.603	0.603	0.000	0.581	0.585	0.003
7	0.671	0.675	0.002	0.609	0.608	0.001	0.586	0.590	0.003
8	0.677	0.683	0.003	0.615	0.607	0.005	0.592	0.596	0.003
9	0.683	0.691	0.004	0.620	0.618	0.002	0.597	0.602	0.003
10	0.690	0.698	0.004	0.626	0.621	0.003	0.603	0.606	0.002
11	0.696	0.704	0.004	0.632	0.628	0.003	0.608	0.611	0.002
12	0.702	0.708	0.003	0.637	0.632	0.004	0.614	0.619	0.004
13	0.709	0.716	0.004	0.643	0.639	0.003	0.619	0.623	0.003
14	0.715	0.719	0.002	0.649	0.648	0.000	0.625	0.627	0.002
15	0.721	0.721	0.000	0.654	0.647	0.005	0.630	0.633	0.002
16	0.727	0.731	0.002	0.660	0.656	0.003	0.636	0.638	0.002
17	0.734	0.737	0.002	0.666	0.659	0.005	0.641	0.644	0.002
18	0.740	0.743	0.002	0.671	0.660	0.008	0.647	0.655	0.006
19	0.746	0.746	0.000	0.677	0.670	0.005	0.652	0.649	0.002
20	0.752	0.752	0.000	0.683	0.678	0.003	0.658	0.681	0.017
Mean	0.693	0.693	0.002	0.629	0.623	0.004	0.606	0.610	0.004

Table-A I-1 Validation of the step length distortion model for three subjects. For each subject, the table presents the actual step length (SL), the avatar step length (Av. SL), and the standard deviation (SD) across 20 distortion levels (%). Values are reported for 20 levels of distortion percentages. The mean values across all levels are shown in the final row.

Reach	Counteracting distortion		Following distortion	
	Endpoint Angle (°)	User Angle (°)	Endpoint Angle (°)	User Angle (°)
1	1.10	-6.19	1.06	-4.66
2	1.94	-4.35	2.05	1.61
3	2.77	-6.13	3.03	-9.52
4	3.85	-5.85	4.01	-8.99
5	5.37	-3.66	4.99	-5.37
6	6.08	-9.61	5.97	-4.12
7	7.00	-7.49	6.96	-3.06
8	8.53	-8.16	7.94	-0.40
9	9.83	-6.02	8.92	6.61
10	10.18	-6.91	9.90	8.63
11	11.64	-7.92	10.89	9.53
12	12.38	-7.92	11.87	12.64
13	13.92	-7.45	12.85	17.48
14	14.21	-8.46	13.83	21.68
15	15.13	-11.11	14.82	20.68
16	16.49	-12.52	15.80	19.54
17	17.56	-12.07	16.78	21.01
18	18.07	-11.21	17.76	19.56
19	19.23	-12.69	18.74	24.36
20	20.15	-13.50	19.73	26.17

Table-A I-2 Validation of the reaching distortion algorithm showing two behavioral patterns: (1) *Counteracting distortion*, where the user responded to the avatar's lateral drift by moving medially, thereby opposing the distortion; and (2) *Following distortion*, where the user initially counteracted the distortion but gradually began reaching laterally in the same direction as the avatar.

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