École Polytechnique Fédérale de Lausanne

Master Thesis

Ensuring self-haptic Consistency for Immersive Amplified Embodiment

Author:
Sidney Bovet

Supervisor:
Dr. Ronan Boulic

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"*Thanks to my solid academic training, today I can write hundreds of words on virtually any topic without possessing a shred of information, which is how I got a good job in journalism.*"

Dave Barry

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Abstract

Computer Science Section

School of Computer and Communication Sciences

MSc in Computer Science

Ensuring self-haptic Consistency for Immersive Amplified Embodiment

by Sidney BOVET

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

This project explores the possibility of distorting movements in the context of a stroke reabilitation task presented as a target-reaching VR serious game.

Acknowledgements

The acknowledgments and the people to thank go here. . .

Contents

1 Introduction

In order to properly introduce this project we need to briefly cover multiple subjects, ranging from stroke rehabilitation to motion capture techniques. All these seemingly different subjects revolve around the idea that we can do something to help stroke patients recover faster by having them participate to serious Virtual Reality (VR) games in which their movements are distorted to keep them motivated.

1.1 Stroke Rehabilitation

As explained by [1], a stroke is a medical condition occurring when parts of the brain stop being provided with proper blood flow. Without such oxygenation, brain cells quickly die. The resulting brain damage may induce various symptoms, such as loss of vision to one side or paralysis. It is the latter that is of interest to us, and more precisely the motor recovery process involved after the stroke itself has been identified and treated. As exposed by [2], there were more than 10 million stroke cases in 2013, which represents an increase of around 60-75% with respect to 1990.

The motor recovery process involves so-called constraint-induced movement therapy, a technique that is at least 100 years old and was proposed by [3]. It takes advantage of neuroplasticity and involves movement exercises of the paralyzed limb. The more the movements are exercised the better the motor recovery will be.

The process as a whole is a long one, involving checkups and exercises at both the hospital and home. Many factors play a role in how successful the recovery process will be, one of them and maybe the most important one being motivation. As argued by [4], the more a patient participates to a rehabilitation task the greater the motor recovery will be. Keeping participants motivated during such tasks is thus essential.

1.2 Virtual Reality

We now jump to a completely different topic, but a careful reader will quickly understand how both are closely linked and of interest to us.

Virtual Reality can be defined as “The computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors.” [5] The most common type of VR device used nowadays are Head-Mounted Displays (HMD), wich are constructed as a screen in front of which two lenses are fixated, allowing the device to be held in front of the eyes while focusing the screen’s content at infinity. Coupled with inertial sensors, such device allows one to look around at a virtual environment. Other VR displays also exist, such as the CAVE: a cube with screen-faces surrounding a user proposed by [6]. In the recent days, companies such as Oculus VR and HTC have begun commercializing HMD and VR becomes more widespread than ever.

1.2.1 Immersion, Embodiment, and Presence

As VR becomes more and more accessible to the general public and broadly used in the industry, immersion tends to be generally accepted as a term describing all of the following concepts.

Immersion

Immersion however has a clear definition offered among others by [7], [8] that we think is preferable to be recalled here: it refers to the capability of a system to deliver a convincing set of sensory stimuli. It is an objective measurement of parameters such as screen resolution, audio equipment, and sensors used.

Presence

What most people tend to call immersion actually is the sense of presence, described by [9], [10] as the "sense of being there". As explained by [11], the central concept of the state of presence is that despite *knowing* that it is a simulation, the user *acts in* and *reacts to* the virtual environment as if it were real.

Embodiment

Embodiment is defined in the field of cognitive neuroscience and philosophy of the mind by [11], [12], and encompasses the relevance of sensorimotor skills and the role the body has in shaping the mind, as well as the subjective experience of using and 'having' a body. It is formally defined by [13] as follows: "E is embodied if some properties of E are processed in the same way as the properties of one's body".

One may from that perspective embody a tool, such as a pen or a hammer, even though that tool is not considered as being part of one's body. As described by [13], the *sense* of embodiment (SoE) refers to the fact that one *feels* such phenomena as opposed to only *knowing* that it exists. As an example, learning that an organ is part of our body makes us embody that organ even though we cannot feel it, whereas felling like the tip of our pen actually is part of our hand creates a SoE towards that pen.

1.2.2 Haptics and Self-haptics

'Haptic' relates to the sense of touch, and more specifically to the one associated to manipulating objects. Feeling the pressure of a sphere between one's fingers when grasping a ball is a haptic feedback. Self-haptic similarly denotes the haptic feedback of touching one's own body part. The feedback thus is dual: by touching one's own arm the brain will receive both the information of the hand touching something and the arm being touched by something. Moreover, before the contact even occurs the brain predicts such self-contact using proprioceptive information about the position of both body parts in space, and is thus very sensitive to such feedback inconsistency.

1.3 Motion Capture

Motion capture can be defined as the action of capturing one's movements in order to reproduce such a motion in one context or another. Video game animations for instance are often performed by actors, whose walking or fighting movements are captured and then played back on the game's characters. The captured movement is often slightly altered, e.g. in order to fit it onto an avatar of different morphology, as proposed by [14].

1.4 Amplified Embodiment

The concept of amplified embodiment can easily be understood as the merging of both section 1.2.1 and 1.3. By capturing one's movements and transposing those on an avatar, we may create a SoE towards that avatar. The goal of amplified embodiment is to distort that avatar's movements by amplifying them while preserving the SoE, which might be partially or completely lost if the distortion is too heavy or non-continuous for instance.

1.5 Serious Games

To conclude this chapter we take a look at another distinct topic, one that closes the loop and creates a connection between stroke rehabilitation, VR, motion capture, and amplified embodiment.

As defined by [15], [16], a serious game is a game that neither has entertainment, enjoyment, nor fun as its primary purpose. Instances of serious games include educational ones such as [17], a 1988 video game where young children could learn the alphabet by exploring a house with a yellow, egg-shaped character and playing various mini games, or the more recent [18], which is a running mobile application using storytelling coupled with GPS localization to keep people motivated at running outside.

We hope that by now the thread linking all of the above subjects is clear enough: we are interested in discovering by how much we can distort one's movements in the context of a VR serious game aimed at motor recovery while altering the sense of embodiment as little as possible, with the goal of keeping the patients motivated at performing the rehabilitation task.

2 Egocentric Coordinates

In this chapter we briefly cover the Inverse Kinematics problem and how its parameters are acquired, and we then dive more deeply in the description of a special coordinate system based on the relative positions of different body parts around a point.

2.1 Motion Capture and Inverse Kinematics

As stated by Paul [19], Inverse Kinematics (IK) refers to the use of kinematic equations of a chain of rigid bodies in order to produce the desired pose of that chain so that it satisfies a position—or goal—for that chain's end effector. Such techniques are useful for instance to compute the joint position of an industrial robot whose task is to tighten a screw at a given location. Another, more interesting application to us of such algorithms is to compute the pose of a virtual body. Such avatar is described as a kinematic chain, and its feet, elbows, knees or head positions are considered as IK goals. An IK solver may be numeric [20], [21], or it may be analytical, such as the one proposed by Molla et al. [22]. In this case, a closed-form expression is provided that takes one or several IK goals as input, and gives a vector of joint positions and orientations to be set in order to satisfy the goals.

These desired positions may be defined by some game engine so that a character points a tool at a desired location, but they are also often obtained using motion capture techniques, as mentioned in Section 1.3. Such techniques usually take advantage of special suits equipped with markers, whose individual positions are acquired either by the marker itself, or using tracking devices. As explained by [23], a suit may for instance be fitted with magnetic sensors and used in a room where a coil emits a given magnetic field, so that each sensor knows its position and orientation relative to the emitting base, acting as an absolute reference. Another way to acquire a position is to place a blinking LED at that location and tracking it using several cameras. If their position is known beforehand (e.g. through space calibration) then the marker's position can be recovered using triangulation.

All the above techniques focus on getting the absolute position (and sometimes orientation) of an IK goal. This is a necessary step for any animation application, but an end effector's position need not be expressed as an absolute value throughout the application's pipeline. The semantic information conveyed by a performer may in fact be better preserved by using an alternative, relative coordinate system.

2.2 Egocentric Coordinates

The idea of using reference points others than the origin of the world's axes in order to describe an IK goal is already a few years old [24], but Molla et al. [14], [25] took it a step further by using one's own body parts as reference points. This allows to correctly map the semantics of performed motions onto avatars of different proportions and sizes. Such body-centered coordinate system is called Egocentric.

A crude body representation is computed from markers placed on the performer. The limbs are represented as capsules while the trunk and head are sampled at multiple locations and then translated into a series of triangles forming a crude mesh. Given such body representation with n body parts, the position $\mathbf{p}_j$ of an IK goal j is then represented as shown in Equation 2.1.

$$\mathbf{p}_j = \sum_{i=1}^{n} \hat{\lambda}(\mathbf{x}_i + \mathbf{v}_i) \tag{2.1}$$

The closest point on surface i is denoted $\mathbf{x}_i$, while $\mathbf{v}_i$ is the relative displacement vector going from $\mathbf{x}_i$ to $\mathbf{p}_i$, and λ is a normalization factor. This last value is computed as $\lambda = \lambda_p \cdot \lambda_\perp$, whose proximity and orthogonality factors are defined in Equations 2.2 and 2.3. $\hat{\lambda}$ is obtained by further linearly normalized λ such that $\sum \hat{\lambda} = 1$.

$$\textbf{Proximity: } \lambda_p = \begin{cases} \frac{1}{\epsilon} & \text{if } \|\mathbf{v}\| \leq \epsilon \\ \frac{1}{\|\mathbf{v}\|} & \text{otherwise} \end{cases} \tag{2.2}$$

$$\textbf{Orthogonality: } \lambda_\perp = \begin{cases} \cos(\epsilon) & \text{if } \cos(\alpha) \leq \epsilon \\ \cos(\alpha) & \text{otherwise} \end{cases} \tag{2.3}$$

In Equation 2.3, α denotes the angle between the surface normal $\mathbf{n}$ at the closes point $\mathbf{x}$ of a body part, and the relative displacement vector $\mathbf{v}$. The presence of ϵ, a tiny constant, helps prevent instability due to floating point precision numbers. The justification for measuring orthogonality is that (1) if a surface normal points at a joint, chances are they are interacting in some way, and (2) orthogonality holds semantic information about gestures, such as holding a hand in front of the heart.

The movement deformation we introduce in this work relies heavily on this Egocentric representation of the IK goals, and more precisely acts on the relative displacement vectors $\mathbf{v}$ described above. The next chapter describes our distortion model, as well as exactly how we adapted the Egocentric formalism in order to apply this distortion to an avatar's movements.

3 Implementation

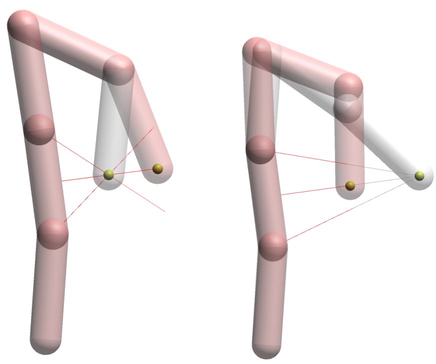
In this chapter we begin by describing our distortion model and what function we used, and then we show how we adapted the preexisting motion capture software in order to obtain the desired distorted behavior.

3.1 Distortion model

As briefly mentioned in chapter 2, we are taking advantage of the Egocentric Coordinate formalism in order to introduce our distortion model. We modify each relative displacement vectors $\mathbf{v}_i$ according to some value γ. A distorted position $\mathbf{p}_j$ is thus obtained using equation 3.1, which has been obtained by modifying Equation 2.1 using a function that we are going to detail in the next few lines.

$$\mathbf{p}_j = \sum_{i=1}^{n} \hat{\lambda}\big(\mathbf{x}_i + D(\mathbf{v}_i, \gamma)\big) \tag{3.1}$$

Figure 3.1 shows an example of a distorted position obtained by changing the length of all vectors $\mathbf{v}_i$.



(A) $\gamma = 3$ (B) $\gamma = -3$

FIGURE 3.1: Two examples of our linear distortion applied to a simple IK arm with multiple segments. The gray lines are the relative displacement vectors and the red ones are their distorted counterparts. Similarly, the gray arms represent the pose the real arm would take whereas the red ones show the two resulting distorted poses.

We will now describe the function we will be using in our subsequent experiment, and then propose a distortion expression that may be better-suited for real-world applications.

3.1.1 Linear Function

For ease of experimentation and understandability, we are looking for a linear function $f(x) = ax + b$. Figure 3.1 gives an example of what we aim to achieve, while Figure 3.2 below gives a more mathematical point of view of the distortion we are looking for, especially in terms of a, the slope of the function. This plot, as well as all of the other plots of this report, were obtained using the Plotly API [26].

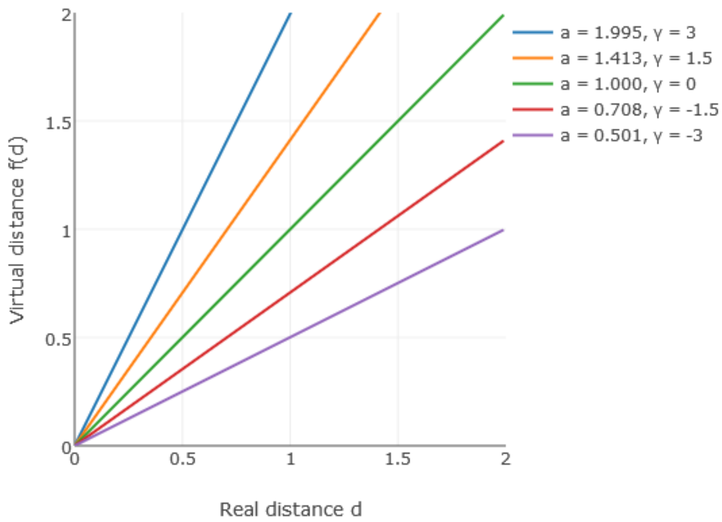


FIGURE 3.2: An example of a few distortion functions for various values of slope a and gain γ.

First of all we want to preserve self-haptic contacts. Such contact happens when a relative displacement vector satisfies $\|\mathbf{v}\| = 0$, which means that we need $f(0) = 0$, and thus $b = 0$.

Intuitively, the slopes should be arranged around $a = 1$, which results in no distortion at all and that we want to correspond to $\gamma = 0$. One can also figure out that there is a correspondence between slopes above and below the line $f(x) = x$. For instance, for a given virtual distance to cover, a slope of 0.5 makes the traveling distance twice as long, whereas a slope of 2 halves the required movement.

Formally, we are modifying each relative displacement vector as specified in Equation 3.1, with γ representing a gain, measured in dB, and f defined by Equation 3.2 below.

$$D(\mathbf{v}, \gamma) = \hat{\mathbf{v}} \cdot \|\mathbf{v}\| \cdot 10^{\frac{\gamma}{10}} \tag{3.2}$$

In this equation, $\mathbf{v}$ is a vector, $\hat{\mathbf{v}}$ is its normalized counterpart, and $\gamma \in \mathbb{R}$. The last factor, $10^{\frac{\gamma}{10}}$, comes from the definition of a gain, in dB [27], based on two values P_1 and P_2 of a single, yet undefined unit:

$$\text{gain} = \gamma = 10 \cdot \log_{10}(\frac{P_1}{P_2})$$
$$\frac{\gamma}{10} = \log_{10}(\text{slope})$$
$$\text{slope} = 10^{\frac{\gamma}{10}}.$$

A value of $\gamma = 3$ thus indicates that the virtual movement will roughly be twice the amplitude of the registered one ($1.995 \approx 2$), while a gain of $\gamma = -3$ means one will have to travel twice as big a distance (0.501) as perceived in order to cover it. Figure 3.1 shows two examples of distortion, and Figure 3.2 gives a few instances of this linear distortion functions with varying values of γ and the corresponding slope a.

3.1.2 Other Functions

Before deciding to use a simpler, thus easier to quantify, linear function for our experimentation process, we tried out different functions that we think are of interest for further applications. Two of these functions are described here as a reference for further investigation.

As for our linear function, we require the distortion to be null around $\|\mathbf{v}\| = 0$. Similarly, we introduce an action range a_r after which the distortion should be null again. The general form of the function applied to our relative displacement vectors then becomes the one described in Equation 3.3.

$$D(\mathbf{v}, s, a_r) = \begin{cases} \hat{v} \cdot \|\mathbf{v}\| \cdot f(\|\mathbf{v}\|, s, a_r) & \text{if } \|\mathbf{v}\| \leq a_r \\ \mathbf{v} & \text{otherwise} \end{cases} \tag{3.3}$$

Note that we changed the 'γ' parameter for 's', which is due to this parameter no longer denoting a cleanly defined gain, but a vaguer concept of strength. Two notable instances of the function f were implemented. They are shown in Figure 3.3 and are described hereafter.

Exponential

Based on an expression proposed by Khoury [28], this function has the following form:

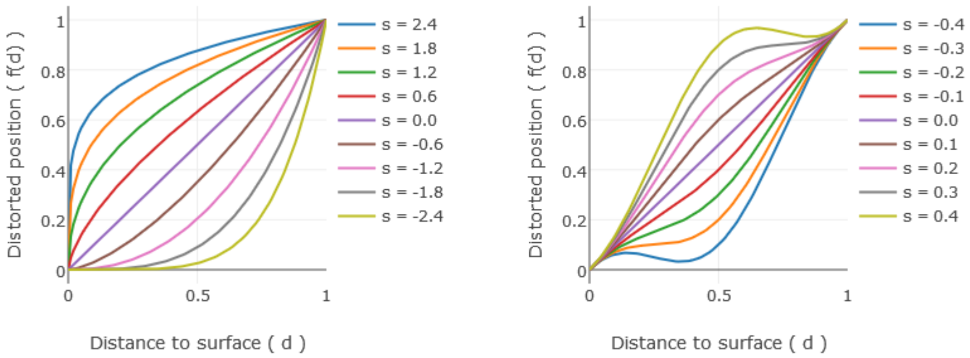
$$f(d, a_r, s) = a_r \cdot \left(\frac{d}{a_r}\right)^{2-s}$$

As one can observe on Figure 3.3, this function has the advantage of smoothly transitioning from a non-distorted position to a maximum discrepancy, and then back to an undistorted position around $d = a_r$.

More observations on the exponential function, particularly on the high velocity discrepancy around the ends of the distorted range.

Cosine

Observations made on the previous function lead us to designing this second function.



(A) Exponential (B) Cosine

FIGURE 3.3: Multiple instances of the two alternative distortion functions we propose in section 3.1.2. Both have been plotted using $a_r = 1$, only varying the strength parameter s.

$$f(d, a_r, s) = \frac{s}{2}\left(1 - \cos\left(\frac{2\pi}{a_r} \cdot d\right)\right) + d$$

Obviously, being smoother in terms of velocity near both ends of the distorted area leads to trade-offs. In our case the function introduces higher velocity discrepancies at other locations, as one can observe on Figure 3.3b. At higher strengths (e.g. $s = 0.4$) the function even forces the virtual hand to go backwards in order to rejoin the real position before approaching a_r.

3.2 Egocentric Normalization Factor

We added one more modification to the definition of the position proposed by [14] which we modified to obtain Equation 3.1, and more precisely the way λ is defined. As originally explained by [25] as well as in Section 2.2, it is computed as the product of two importance factors, proximity and orthogonality, respectively denoted λ_p and $\lambda_\perp$.

The former importance factor was initially defined as $\lambda_p = \frac{1}{\|\mathbf{v}\|}$. In practice we find that this formula does not give enough importance to nearby body parts, and we decided to change it slightly as $\lambda_p = \frac{1}{\|\mathbf{v}\|^2}$. –Mention angle solide.–

3.3 Reachable Sphere

A few words on the concept of reachable sphere and how it might help at the limits of the reachable space.

4 Experiment

We are trying to estimate the limits of self attribution of a distorted movement. We will do so by estimating the just noticeable difference (JND) in visual stimuli discrepancy. This means estimating the just noticeable *distortion* made to the movement and hence the visual stimuli. The JND is estimated by using the adaptive staircase method introduced by [missing ref].

This method tries to estimate the JND by finding an upper and a lower bound for that value. These are found by changing the intensity of the distortion, based on whether the subject judged the last trial as distorted or not, and the JND is computed as the mean of the last few staircase turns (i.e. going from an increasing trend to a decreasing one or vice-versa). The detection judgment is gathered using a Yes/No prompt called the detection question : "Did the movements you saw exactly correspond to the movements you performed?"

4.1 Just Noticeable Difference

The JND will be measured in term of γ, the gain of the distortion function introduced in Equation 3.2. In general, if $\gamma = -3\,\mathrm{dB}$ the subjects are hindered by having to travel two times the distance between the targets, whereas if $\gamma = 3\,\mathrm{dB}$ the movement will be amplified and the required motion will be reduced by 50%.

Due to the nature of the Egocentric Coordinates and how the distortion is applied (respectively detailed in Chapters 2 and 3), this will not exactly be a metric of the difference in the distance that the subjects have to cover in order to reach the target, such as the metric used by [11] [plus other refs]. It however gives a good understanding of the strength and the effect of the applied distortion.

4.2 Hypothesis

The hypothesis we have for the experiment is the following:

H1: The absolute value of the JND will be higher when the distortion is positive.

H2: Do we need more than one hypothesis?

4.3 Equipment and Software

The HMD used for this experiment is the Oculus Rift in its first consumer version, with a resolution of 1080×1200 pixels per eye and a refresh rate of 90 Hz.

Some more words on head and body tracking, with references to [22].

4.4 Experiment design

We manipulate three factors: the sign of the distortion (positive or negative), respectively yielding a helped and hindered movement, the starting value of that distortion (either 0 or 9 dB, and the target sequence (see below). Chapter 3 gives a complete overview of the concept of distortion and its sign, as well as how it is implemented.

4.4.1 Task

While the whole set of IK goals will be distorted during the experiment, we will be focusing on the dominant hand movement. The task is performed in a seated position in order to avoid any unnecessary movement of the lower limbs, and has the subjects reach three targets. One of them may be in the air in front of them, while the starting and finishing location is the same relative to their skin. The reaching task is performed with the directing hand, and the subjects are instructed to keep their other hand at their side.

There are four different target orders: **Chest-Air-Chest**, **Leg-Air-Leg**, **Chest-Leg-Chest**, and **Leg-Chest-Leg**. Both chest and leg targets are located as depicted on Figure 4.1 and are picked according to the subject's handedness: left-handed subjects for instance will have to reach for their left thigh and right shoulder. The first target to be displayed, T_1, is always one on the skin and requires the subjects to perform a self-contact in order to activate it. After a random time between 200 and 300 ms, the target activates. Then the subject moves the hand to the next target, which activates after 100 ms. Once this is done the subject goes back to T_1, and the detection question is finally asked.

If the sequence requires an intermediary air target, its position is computed such that the subjects have to move a predefined distance $d = 75\%$ of arm length between T_1 and T_{air}. Given that a whole sphere of positions is possible, and in order to disambiguate that position, we require that T_{air} is also at the same distance d from the third, unused target T_3. The air target position therefore is on the intersection between the two spheres of radius d centered on T_1 and T_3, and we chose the topmost position as a reasonable last disambiguation criterion. Figure 4.1 shows how such position is computed.

One experiment—or staircase—run consists of a reaching task, followed by the detection question. Based on the answer to this question, the experiment software modifies the distortion for the next staircase run as follows:

`"Yes"`	The discrepancy is increased.
`"No"` and $\gamma \neq 0$	The discrepancy is decreased.
`"No"` and $\gamma = 0$	The parameter is not changed[1].

The amount of each increment or decrement is dynamic: it starts at 0.5 and is halved after the first staircase turn. That value is then kept for the rest of that staircase. The staircase is completed either when the subjects change direction 7 times or when they performed 20 trials in that staircase.

[1] We do not change the distortion in this case because this would invert the sign of the distortion, thus introducing a different distortion.

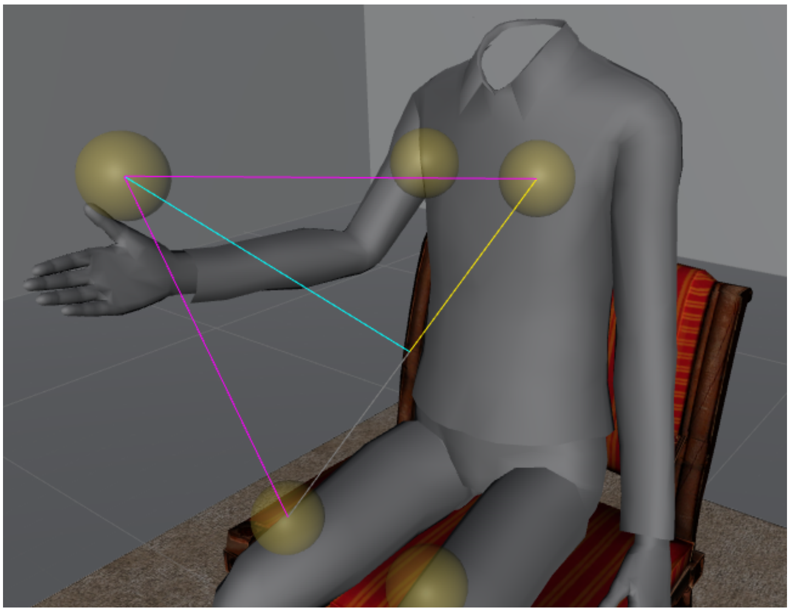


FIGURE 4.1: An example of target placement with lines showing how its position was reconstructed. The magenta lines are the one of desired length.

4.4.2 Procedure

The subjects are welcomed and introduced to the protocol described here, and then introduced to the tracking equipment. A consent form is signed and a characterization form is then filled in by the subjects. The questionnaire features background questions such as age and handedness, but also regarding any previous VR experiment or experience with HMDs. They are then asked to remove their shoes and helped in putting the motion capture suit on. A calibration is then performed as described by [14] and mentioned in Chapter 2.

Before beginning the actual staircase trials, a familiarization phase takes place. The subjects goes through two shortened staircases with constant distortion. The first one has no distortion at all while the second has a big one. The subjects are instructed to always answer "Yes" during the first staircase, and "No" during the second one, so that they become familiar with the whole procedure.

More on the next steps later.

4.5 Subjects

A few physical limitations will be applied to filter the subjects of this experiment. They will be required to be right-handed for ease of software development, and will need to be both smaller than 180cm and have a body mass index between 18 and 27. The latter two criteria are due to our motion capture equipment and especially the suit on which the markers are placed.

We also require that they have a normal or corrected to normal vision, and be fluent in both written and spoken English.

5 Results and Discussion

5.1 Distortion

Examples of distortion and the resulting movements have already been shown on Figure 3.1. We propose here a more concise summary of our results and a discussion of them.

5.2 Set of Tools

–Mention of the issues encountered with the set of tools when used in live conditions–

6 Conclusion

6.1 Further Work

–Description of what are the next steps, namely cleaning the toolset, and running the pilot + adjusting the experiment and actually running the experiment–

A Questionnaires

All the questions used will be displayed here.

A.1 Characterization

The characterization questionnaire

A.2 Redirection detection

The yes/no question with screen shots.

A.3 Embodiment

The embodiment questionnaire

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