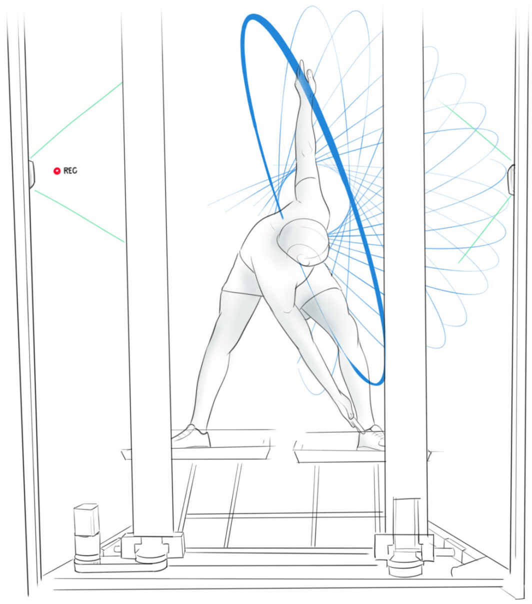
Fitness 2.0

Enabling a safe experience
in a *VR*-based robotic platform



TU Delft

ETHEREAL matter

Master thesis

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To my parents, brother and girlfriend who gave me unconditional support along my university studies.

And specially grateful to the marvellous people that I had the opportunity to meet and accompany me during these 2 years at Delft, both in the academic and personal environments.

Executive summary

Providing a bodily injury-free experience might be a promising opportunity for the adoption of VR and force feedback-based equipment in a gym context. Nevertheless, it is still uncertain how these systems could compromise the users' physical state and how they should react a posteriori.

This Graduation project begins with the exploration of the bodily injury risks associated with the Ethereal Engine, an ultimate VR-based equipment that seeks a revolution in the fitness industry. Resulting in four different clusters -collision, posture, balance loss and long-term exposure-related risks-, a study on the current market-ready technologies that could minimize these risks is performed together with an assessment on how safety can be boosted while keeping the experience's engagement.

Thanks to the research, posture evaluation is selected as the challenge with a differential potential over the rest to bring Ethereal Engine to the next level, providing an experience in which bodily injury risks could be reduced, motivating users to adopt better postural habits when working out. Right after, a design vision is formulated, emphasizing the need for inspiring users to self-correct their posture instead of imposing rules in order to avoid possible immersion breakages.

In this context, three concepts are proposed, which present different feedback alternatives that vary in terms of explicitness, immediacy, and strictness. However, a priori there is no clear answer on which of these alternatives could most positively affect the experience. To overcome the knowledge gap an experiment that not only assesses the performance of the 16 participants but also their perception of the understandability, usefulness, performance, posture correction, general engagement, confusion and criticism of the feedback is conducted. During three different experiments where different feedback alternatives are assessed -immediate visual clues, statistics after certain repetitions, and immediate pop-up messages- participants are asked to perform 10 squats while lifting a water jug and receiving different scores depending on its displacement.

In order to do so, a partial prototype that allows for the first time to experience certain functionalities of the Ethereal Engine is developed. These functions are: a) a hybrid MoCap system that merges a Oculus Quest headset with a multi-camera-based skeletal tracking system -named MoCapForAll-. ; b) a calibration process that adjusts the range of motion according to the participant's height; and, c) a demo game that enables a more intense workout while keeping track of your posture while squatting.

After discussing the results, including a calibration process that enables fair competitiveness and feedback at three different levels to communicate diverse information are spotted as desired features to include in the Ethereal Engine. Through these recommendations a virtual trainer that inspires users to self-correct their posture will be possible, and, subsequently, enabling a bodily injury-free experience.

Content

Figure 1.- Close up of the US prototype's hand
grip assembly from September 2021

- C H A P T E R 1 -

Introducing the project

The Ethereal Engine is a virtual reality gaming environment with robotic components that provide counterforce to the user, enabling an immersive work-out with no precedent. As it is discussed in this chapter, keeping the user safe throughout their work-out runs the risk of breaking the immersion. The questions related to tackling this challenge will be outlined, as well as the approach to answering these questions.

Lastly, the reader will be introduced to the project assignment, offering the most concise explanation possible to understand the operational functioning of the Ethereal Engine and the circumstances surrounding the project.

1.1 The Ethereal Engine

1.1.1 Product/Market/ Context Need

Worldwide obesity has nearly tripled since 1975 and is still growing (WHO, 2021) . More than a quarter of the world's adult population is physically inactive (WHO, 2021). Physical activity has been shown to have significant health benefits for hearts, bodies and minds, as it prevents non-communicable diseases, reduces symptoms of depression and anxiety and improves overall well-being (WHO, 2021). Still, more than 80% of the world's adolescent population and 20% of the adult population are not sufficiently physically active (WHO, 2021). In particular, technological advancements in the gaming industry have led to a larger number of people, including children, spending time on video games rather than going for physical exercise.

Interactive fitness products try to fight this increasing problem by introducing technology to the fitness industry market, making workouts safer, more fun and flexible. This so-called *exergaming* is considered a specially promising industry as physical exercises are combined with video games to help people build up their strength and improve their fitness levels.

One of the companies involved in this *exergaming* industry is Ethereal Matter, whose vision is to create "*a full-body, intelligent fitness platform enabling immersive virtual-physical interaction, adaptable to the range of humanity who desire the benefits of improved health*". To achieve this vision, a prototype called the "*Ethereal Engine*" was created.

1.1.2 The machine

The Ethereal Engine emerges as a platform providing users with an unprecedented way of experiencing fitness and virtual reality - or *VR*-. An experience possible through a machine that integrates *VR* and Motion Capture - or MoCap- technologies and which consists of two robot armatures mounted in a static structure that delivers resistance to activate the muscles.

This concept is based on the interaction of the real-time measured force exerted by the user and the virtual world physics. In addition, the *VR* headset arises as the channel to get immersed in the virtual world, whereas the MoCap system as a tool to track and replicate in the virtual context the position of the user. Lastly, the machine mounts two oscillating foot platforms enabling a wider range of workouts.

All the cited elements constitute the engine, where end-users exercise and play different games while keeping track of their personal progress, competing with their personal records and even in multi-player mode challenging family and friends. Note that the Ethereal Engine should be understood as a platform which gathers users and developers rather than a product with predefined and limited functionality.

1.1.2.1 Targeted market

Conceived as a daily workout alternative, gyms are targeted as market entry points. Due to the multiple technologies involved, the market price estimation of the Ethereal Engine is of the order of 15.000 - 20.000 US dollars. To effectively tackle this limitation, offering the Ethereal Engine by means of a premium gym subscription is considered. The additional cost

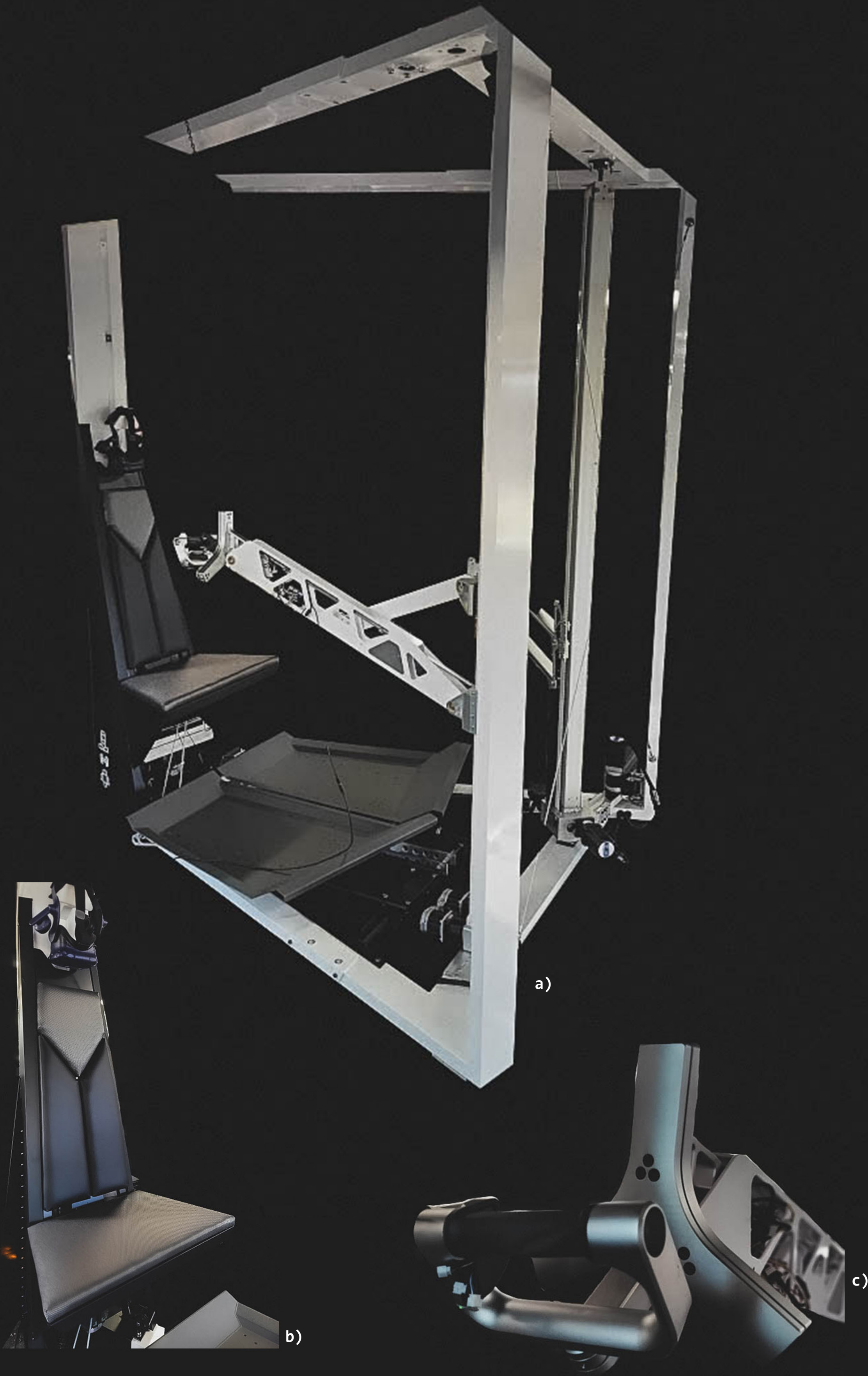


Figure 2.- Ethereal Engine US prototype from January 2022 a) Full assembly b) Seat and headset hanger c) hand grip assembly

is still uncertain, but the square metre amortisation in gyms is being explored to estimate a price that would both attract gym owners and guarantee the profitability of Ethereal Matter.

Other market opportunities such as personal use and medical applications are being considered for low-cost and high-end versions of the engine respectively, Due to the considerable investment necessary to purchase the engine, price optimization is considered a key requirement to access the mentioned markets.

1.1.3 Current Interaction

When it comes to explaining the envisioned interaction with the machine, storytelling offers an effective solution to get the Ethereal Engine experience across. Down below, a modified version of the story used by Scott Summit to get the machine's possibilities across is included:

You work long hours in a corporate setting, counting down hours to 18:00, your hour of fitness. When you arrive at the gym, you step in your selected Ethereal Engine, put on your headset, and immerse. You glance down at your digital body and perceive an unusual weight moving your arms. You look at them and see a pair of wings. You give a strong upward press, followed by a solid downward pull, and you lift gently from the ground. A few minutes later, you feel like a good moment to change exercise and switch to a speeder exercising a different group of muscles. After 45 minutes, you have completed your daily workout, willing to repeat the experience soon -see Figure 3-.

1.1.3.1 Current interaction problems

Although the aforementioned story seems plausible, not all are roses and unicorns. The following story sheds light on the current interaction limitations tackled in this project.

You enter for the first time the Ethereal Engine, and see yourself with the previously mentioned pair of wings. You give a strong upward press, followed by a solid downward pull, and you lift gently from the ground. You still are getting used to your new limbs, and suddenly you are dangerously about to lose your stability. A second later, you perceive some adjustment in the graphical interface and feel how the machine is adjusting its behaviour to keep you safe without exerting extra force. You feel relieved and continue enjoying the experience.

This story illustrates one among the risks possible to experience in the Ethereal Engine. However, the behaviour it should adopt to avoid or mitigate these risks is still uncertain and unexplored. Nevertheless, it can be claimed that getting bodily injured would have a negative effect on the engagement of the engine.

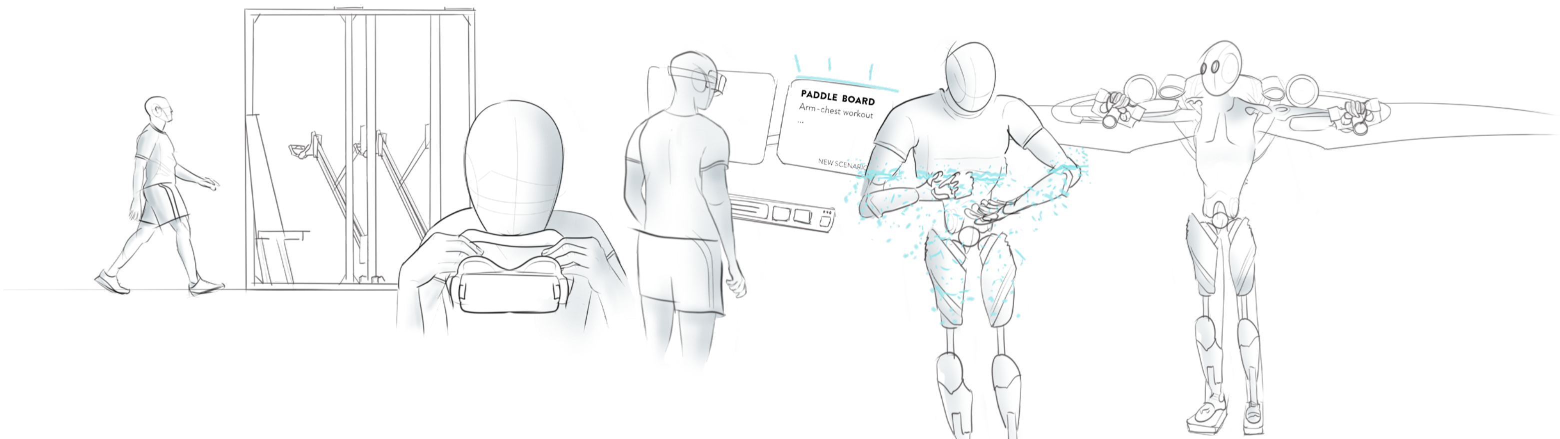


Figure 3.- First steps on the interaction with the Ethereal Engine. From the physical product to the *VR* world

1.2 Problem definition

When it comes to envisioning the desired robot-human interaction of the Ethereal Engine, three forces emerge as antagonistic but also necessary requirements to keep the user attracted. These are **the realism** of the experience, **the enabling of intense workouts**, and **the physical health** of the user. A balanced combination of these three key features is essential to let users achieve their workout objectives. See *Figure 4.*

For the time being, from Ethereal Matter, the product design has been oriented towards the withstanding of the forces exerted by the user, prototyping a robust system that enables intense workouts. The proposed project aims to dive a level deeper into the design of an interaction that will reduce the risks of getting injured while keeping the experience challenging and realistic. Augmenting safety is spotted as a competitive advantage for Ethereal Matter, which could help in the adoption of robotic technologies in gym contexts by improving users' perception of such products.

This challenge is tackled considering the use of the technologies already implemented on the Ethereal Engine and focussing on how to make the system safer while keeping the experience engaging. Therefore, the main question tackled in this design project is: **how to reduce the bodily injury risks during the interaction with the Ethereal Engine while providing an engaging experience.** Some sub-questions derived from the aforementioned question are:

What are those bodily injury risks ?

Can we make use of positional/force/ virtual world data in order to avoid over-strain and bodily injuries?

And if so, what is the desired human-robot interaction?

Should it provide feedback through the *VR* interface, a physical response, or a combination of both?

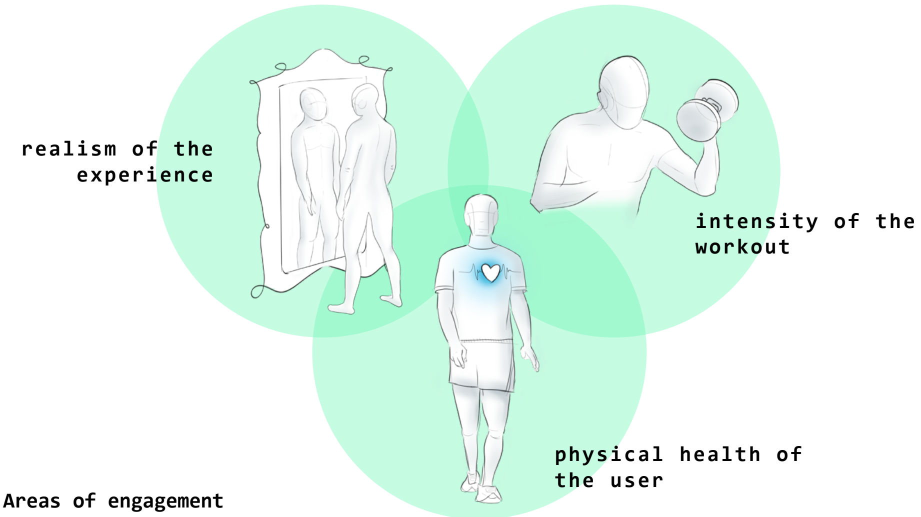


Figure 4.- Areas of engagement

1.3 Assignment

The assignment consists in designing a solution to reduce the bodily injury risk present during the interaction with the Ethereal Engine while keeping it challenging and realistic, by means of a system (physical product and data model) that enhances its perception and gives certain flexibility to the behaviour of the Ethereal Engine when the user could get injured. Simplified functionalities of this system will be tested and prototyped.

With regard to the process flow, it begins with an initial research phase focused on the definition of the bodily injury risks associated with the current activities/games developed for the Ethereal Engine, followed by an exploration of the state of the art of technological opportunities to mitigate these risks corresponding to *Chapter 2: Understanding the need* and *Chapter 3: Exploring opportunities* respectively. This technical exploration is complemented by an exploration of possible qualities by means of which the behaviour of the engine would remain engaging when incorporating safety measures.

Next, a convergent phase toward three different concepts to be further tested is conducted -see *Chapter 4 Synthesizing towards a challenge* and *Chapter 5 Concept design-.*

As a final delivery, partial prototypes used to test features of the proposed concepts are included -see *Chapter 6 Prototyping and Chapter 7 Evaluation-* , and subsequently, a final reasoned concept choice is discussed - see *Chapter 8 Final concept-*.

1.3.1 Background

This journey started during Q1 of the 2021/2022 academic course, with the initial goal of generating a replica of a working prototype in the US, that would actively incorporate upgrades to optimise the product in terms of performance, weight, cost and market strategy. Resulting from that collaboration, a prototype oriented towards cost reduction started to take shape: *the Delft Engine.*

1.3.2 Stakeholders

Stakeholder management and coordination play an important part in the project. Since the project sets up an intercontinental collaboration between Ethereal Matter and the Technical University of Delft, shared but also individual expectations emerge from each of the involved parties.

This Graduation Project, firstly, aims to provide Ethereal Matter with a proposal of a bodily injuries-free robot-human interaction to bring the user experience to a higher level. In the second place, it has to be understood as part of the journey towards a first prototype in Delft -the *Delft Engine-*, targeted as a short-term need for the University to engage more students.

Thereby, the success of managing client expectations not only depends on my individual performance, but also on the capabilities to coordinate the development of a common and coherent prototype with a team of students following the course: Advanced Embodiment Design -*AED-*, and Moritz von Seyfried, an Integrated Product Design master student working in his graduation.

The Technical University of Delft facilities, such as the *PMB* and *Dream Hall* production workshops are targeted as valuable resources at disposal.

Figure 5.- Delft Engine concept. November 2021

ENGAGING?
SAFE?

Figure 6.- Experimenting with Motion Capture in the Delft Engine partial prototype

- C H A P T E R 2 -

Understanding the need

Providing a bodily injury-free experience might be a promising opportunity for the adoption of *VR* and force feedback-based equipment in a gym context. Nevertheless, it is still uncertain how these systems could compromise the users' physical state and how they should react a posteriori.

This chapter sets an initial framework, cataloguing the risks involved in the interaction in a collision, posture, balance loss and long-term exposure-related. Additionally, it includes an elaborated description of the risks present in the interaction with the Ethereal Engine. Finally, the current system architecture is presented, analysing how components of the current US prototype have an impact on safety.

2.1 Exploring the need

Due to the unique nature of the Ethereal Engine, there is not a counterpart product that provides the same functionality. In fact, for the time being, consumer-ready mechatronic systems for *VR* fitness which can provide high-force physical feedback are quite limited. The *Black Box* is one of those rare pieces of equipment that could provide a similar full-body *VR* training to the one the Ethereal Engine pursues ("*Black Box VR Fitness - Immersive Gym and Gamified Fitness Experience*," n.d.). Diving deeper into this system's operational mechanics, by means of motors and cable-based drive systems variable resistance is conferred when pulling, and no feedback when pushing.

Conversely, the counterpart product spectrum broadens when exploring systems without *VR* technology. ("*Tonal | The World's Smartest Home Gym and Personal Trainer*," n.d.) ("*Proteus Motion*," n.d.) Among them, *The Proteus System* is highlighted due to the similarities in the mechanical requirements with the Ethereal Engine. However, none of this integrates Motion Capture technology to keep track of user position, which is proposed to be one of the main sources to reduce bodily injuries.

Owing to the limited information on the risks involved in robotic systems that provide high force feedback the following questions are formulated:

i. What is the scope for risk assessment?
ii. What are the Ethereal Engine's bodily injury risks for the selected scope?
iii. What does the current system architecture look like? And how do components have an effect on safety?

2.1.1 Injury risks exploration, understanding the machine's limitations

Bodily injury risk prediction might be beneficial to guarantee the physical safety of the user. The recent completion of Ethereal Matter's fully working prototype and the bare documentation of robotics applied on fitness contexts reveal the scarcity of knowledge in this area. In fact, it is still an open question what risks the interaction with the Ethereal Engine does entail. The proposed exploration aims to identify risks that could result in bodily injuries affecting the user-robot interaction in a negative manner.

The method starts with the scope definition, shedding light on the application explored along this study.

Next, through observing existing recordings of users interacting with the Ethereal Engine potential injury situations are spotted. Additionally, through conversations with the client, risks are complemented and contrasted with the client's knowledge and assumptions.

Lastly, *The Wizard of Oz* testing is performed to get a better feeling of the intrinsic characteristics of certain risks -see *Figure 7*- (van Boeijen et al., 2013).

2.1.1.1 Scope

Due to the wish of releasing the Ethereal Engine as a fitness platform that will enable developers to tweak the machine, most of the risks will depend on the features of the workout demanded by currently non-existent games. The envisioned multiple use cases will require to analyse from high precision low force applications -e.g. medicine- to demanding force feedback situations -e.g. fitness-.

Due to the differences that the wide range of envisioned use cases require, it is decided not to explore the full-motion capabilities of the machine, the currently developed games instead. This decision is based on the short-term need of showcasing a smartly designed game, prioritised over the comprehension of whole-body motion and posture resulting in guidelines for further game development.

Giving certain background information on the gaming experience, the most up-to-date game gathers two clearly distinguishable workout exercises. The change of exercise is controlled by the user and is communicated through the *VR* graphic interface by means of the visualisation of a transformer that turns into a flying machine -named ornithopter- and a flying motorbike -named speeder-. Each of these virtual equipment involves a different control method, with counterpart gym movement for the upper and lower limbs, as shown in *Figure 8.*

Figure 7.- The Wizard Of Oz experiment

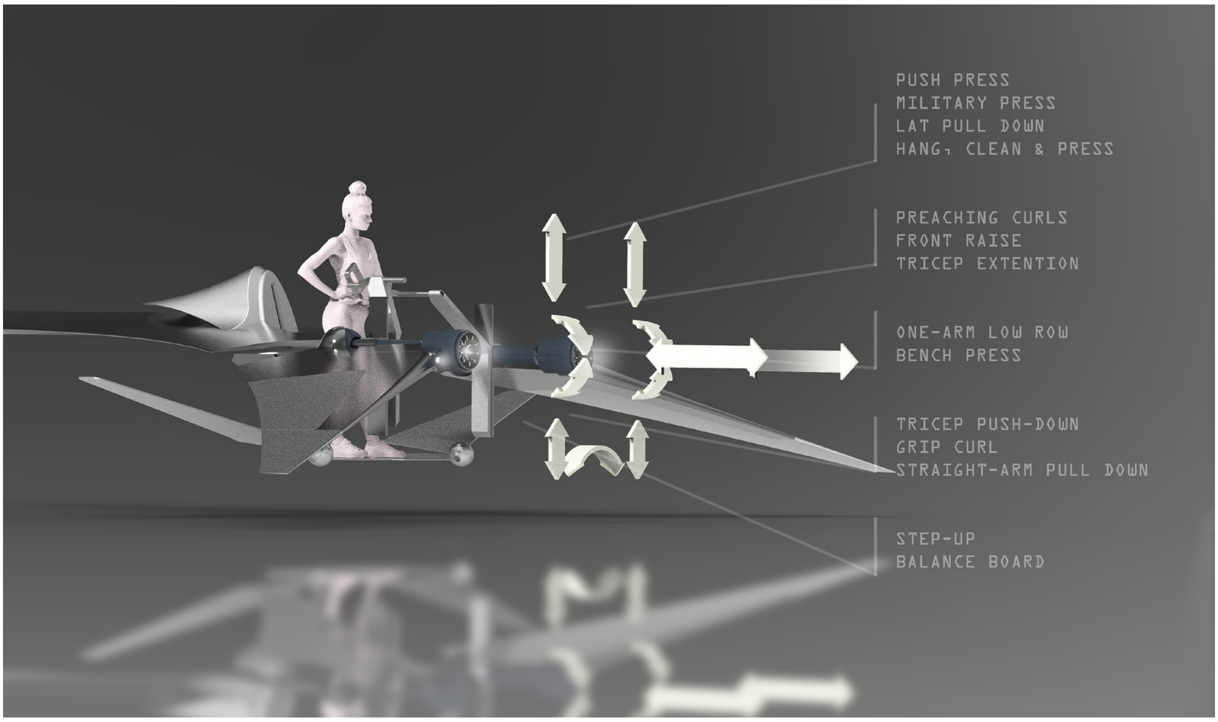
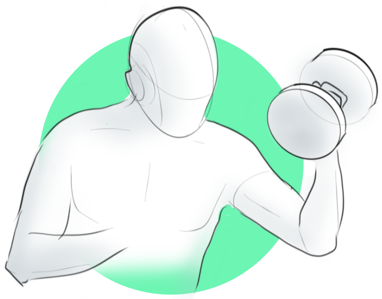


Figure 8.- Motion capabilities of the transformer and counterpart gym moves

Figure 9.- Representation of the envisioned *VR* experience. In the top right corner a second flying machine echoes the multi-player possibilities of the experience

2.1.1.2 Injury risks

Risk detection broadens the spectrum of necessary challenges to be tackled in order to provide a safe interaction. The spotted risks and the current solutions are shown in *Figures 10-16*. These risks are catalogued in four groups: collisions, posture, balance and exhaustion-related. Being aware of the risks involved, a selection of one of these categories based on the relevance for the company and the existence of human-robot interaction tensions is included in *Chapter 4: Synthesizing towards a challenge*.



People lifting excessive weight

Users can get injured if they exceed their physical limitations.

- Current solution: There is not any tweak implemented. The machine reads the physics of the *VR* world and results in a certain armature movement.

Figure 10.- Risk 1

People exercising in bad postures

Bad postured maintained repeatedly along workout sessions can harm users. Experiencing a new *VR* world could dangerously make user avoid their physical limitations.

- Current Solution: The skeleton tracking data is used to replicate the user in *VR*, but not to assess posture.
- There are already research projects on postural analysis based on MoCap data (rehabilitation purposes), the next step is to make use of it to adapt force feedback systems.

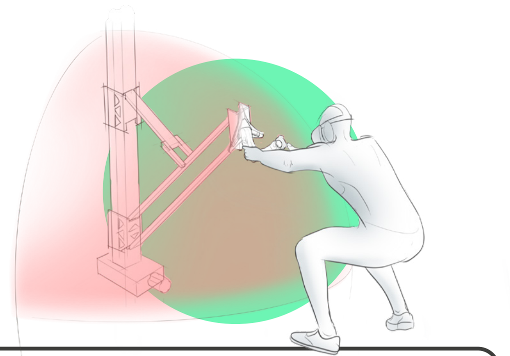
Figure 11.- Risk 2

Exhaustion due to long term exercising

Users' physical capabilities vary along the workout, and the current setup does not incorporate adjustments over the training session.

- Current solution: There is not any tweak implemented.

Figure 12.- Risk 3

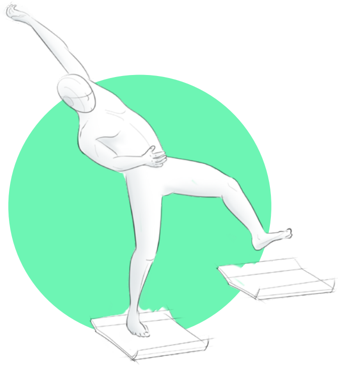


Keep out zone understandability

Considering the fact that due to the mechanical design the machine presents a zone out of reach, how this limitation is communicated to the user plays an important role, to avoid getting injured.

- Current Solution: Current games are designed to keep users operating far from that conflict zone. In addition a switching keep out zone is being explored to tune the physical machine to the workout range of motion.

Figure 13.- Risk 4

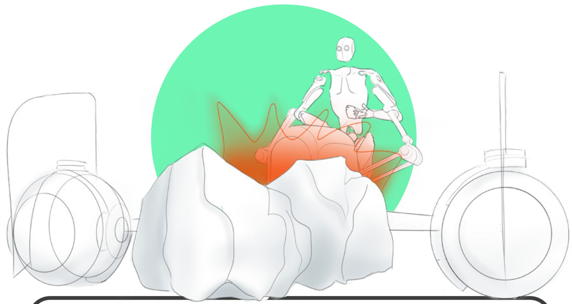


People falling from the foot platforms

The motion of the platforms could destabilize the user. Moreover, being the platforms lifted from the floor, users could fall from a considerably high height if they do not keep track of these platforms position.

- Current solution: There is not any tweak implemented. The maximum height difference between platforms is derived from the physical limitations of the motion mechanism.

Figure 14.- Risk 5

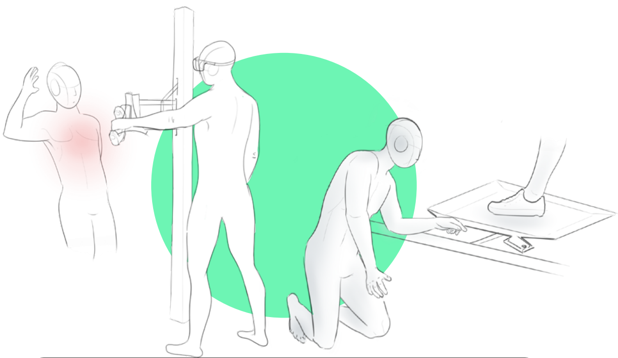


Wall hit when navigating

Hitting walls either mounted on the speeder or ornithopter could user make experience an abrupt crash, which could harm them.

- Current solution: In the speeder game, when users hit walls with a speed above a certain threshold, the user is moved to a different space and re-spawn after a few seconds.
- Whereas in the ornithopter, they re-spawn immediately.

Figure 16.- Risk 7



Interaction with bystanders

So far there is not a script on *Unity* that filters user from bystanders. But since this feature can be integrated in the current design, there are certain doubts about how the user acknowledges the presence of these bystanders and how the Ethereal Engine guarantees that nobody gets injured while mechanisms are moving.

- User moves the grip laterally, and consequently the robotic arms rotates crashing with bystanders.
- The bystander decides to touch the carriage mount or feet platform, resulting in injury. The astuteness of the US population finding gaps in the legislation to get financial compensations is a pertinent risk to keep in mind.

Figure 15.- Risk 6

Moving to *The Wizard of Oz* testing, it consists of two experiments in which certain machine's features are simulated. For a first experiment in which the risk of stepping out from the platforms wants to be evaluated, the rigid part of a sofa is used as a platform. Since using external participants could be considered unethical, the designer itself takes the risk. In a second experiment, using the end effector of the robot the robot-human tension is assessed. For this purpose, the designer acts like a robot and applies certain resistance simulating the directional opposition that would be executed in the games. 3 participants take part in this last experiment.

The conclusions drawn from *The Wizard of Oz* experiment are listed below:

- First, while wearing a *VR* headset, users are no longer aware of the real-world environment. What leads users to lose real-world references not only is the fact that they do not receive information about both static and dynamic objects in their surroundings -as if they were blindfolded-, but also the *VR* information they receive experiencing a completely different world.
- In the aforementioned context, including real-world references could reduce the gap and let the user have some points of reference in case the performed activity puts users in danger. However, references might be limited not to break the immersion.
- In the third place, different people require

different settings. After trying out the simulated robot-human tension with 3 participants with heterogeneous body sizes, it is concluded that the maximum applicable force varies depending on the person but also the posture they adopt.

Conducting an early feasibility assessment on how this adjustable experience could be incorporated into the Ethereal Engine, considering the current setup, some adjustments could be done through *Unity*, setting different conditions depending on the user's capacity. *Chapter 4: Synthesizing towards a challenge* elaborates on this idea.

2.1.2 System architecture, understanding the machine's operation

The control of the Ethereal Engine is centralised in *Unity*, a versatile cross-platform game engine based on C# scripting language (*Unity*, n.d.). Within this context, the physical world input -e.g. exerted force and position data- accesses the virtual environment and the resulting output from both worlds' interaction is materialised as physical resistance through motors actuating a mechanical system.

Considering the multiple components involved, not only understanding the operational methodology but also realising how components have an effect on safety plays an important part in further developing the Ethereal Engine. *Figure 17* includes a system architecture diagram illustrating the interaction among components.

2.1.2.1 Force control

The measurement of the executed force and its direction is performed by means of three load cells distributed in a triangular shape. These sensors detect load variations of 0.01kg, being reliable enough for generating smooth motion.

Three stepper motors control the motion of the robotic armature in the three-dimensional space. Together with a free motion gimbals mechanism -which incorporates 2 additional rotational degrees of freedom- a comfortable range of motion is obtained.

The main limitation of this force input-output system regarding safety derives from the misuse of the robotic arms. If someone hits the robotic arms when a certain user is playing, the load cells will measure the combination of forces applied, leading to an unexpected reaction that could harm the user.

2.1.2.2 Position tracking

For position tracking instead, a hybrid solution is implemented. In the current setup, the *HTC Vive* headset and trackers are used for head and hands tracking. Secondly, the prototype mounts *Kinect Azure*, an *RGB-D* sensor distributed by *Microsoft*, to track the rest of the body. Additionally, through Inverse Kinematics procedure, inconsistencies derived from measurement errors or occlusion problems are corrected in elbows and knees.

The accuracy of the motion capture system affects the user replication in *VR*, which subsequently results in a reduction of the risk of hitting yourself due to an unrealistic visualisation of your physical boundaries. This offset can even get worse, because the MoCap system does not incorporate a solution to recognize the user from other people in the near surroundings.

2.1.2.3 Controllers

The navigation through the interface is performed by a conventional gaming controller mounted in the end effector of the robotic arm, including a joystick and trigger.

As a last component of the grip, a solution to escape the virtual experience is included. Called dead-man switch, is a safety mechanism for critical moments in which the user feels overwhelmed. By releasing the grip a pressure sensor changes its binary state, stopping the force control system. This solution lays the assessment of risks upon the user, does not take advantage of the smartness of other components and could lead to frequent breakages of the immersion.

2.1.2.4 Delft Engine variations

The *Delft Engine* presents minor changes, taking other exploratory paths, with the ultimate goal of integrating intercontinental knowledge into one successful product. Above, the changes with a major influence on this project are listed.

Firstly, a MoCap solution based on multiple *RGB* sensors named *MoCapForAll* is considered a solution to eliminate occlusion at a cheap price. This software makes use of multiple images to detect human positioning by means of a *Machine Learning* -or ML-based prediction model.

Secondly, for tracking hands the system makes use of motor's encoders and *Inertial Measurement Units* - or *IMUs*-, providing positional and rotational data respectively. Thereby, occlusion and the accuracy limitation of MoCap for hand detection is overcome.

However, by the start of the project, these are merely conceptual solutions that have not been proven. In fact, the Delft Engine prototype solely contains the hand grip assembly - or end effector of the mechanical system- and a structural frame where the components will be mounted. In *Chapter 6 Prototyping* a section describing the efforts carried out towards the assembly of the Delft Engine is included.

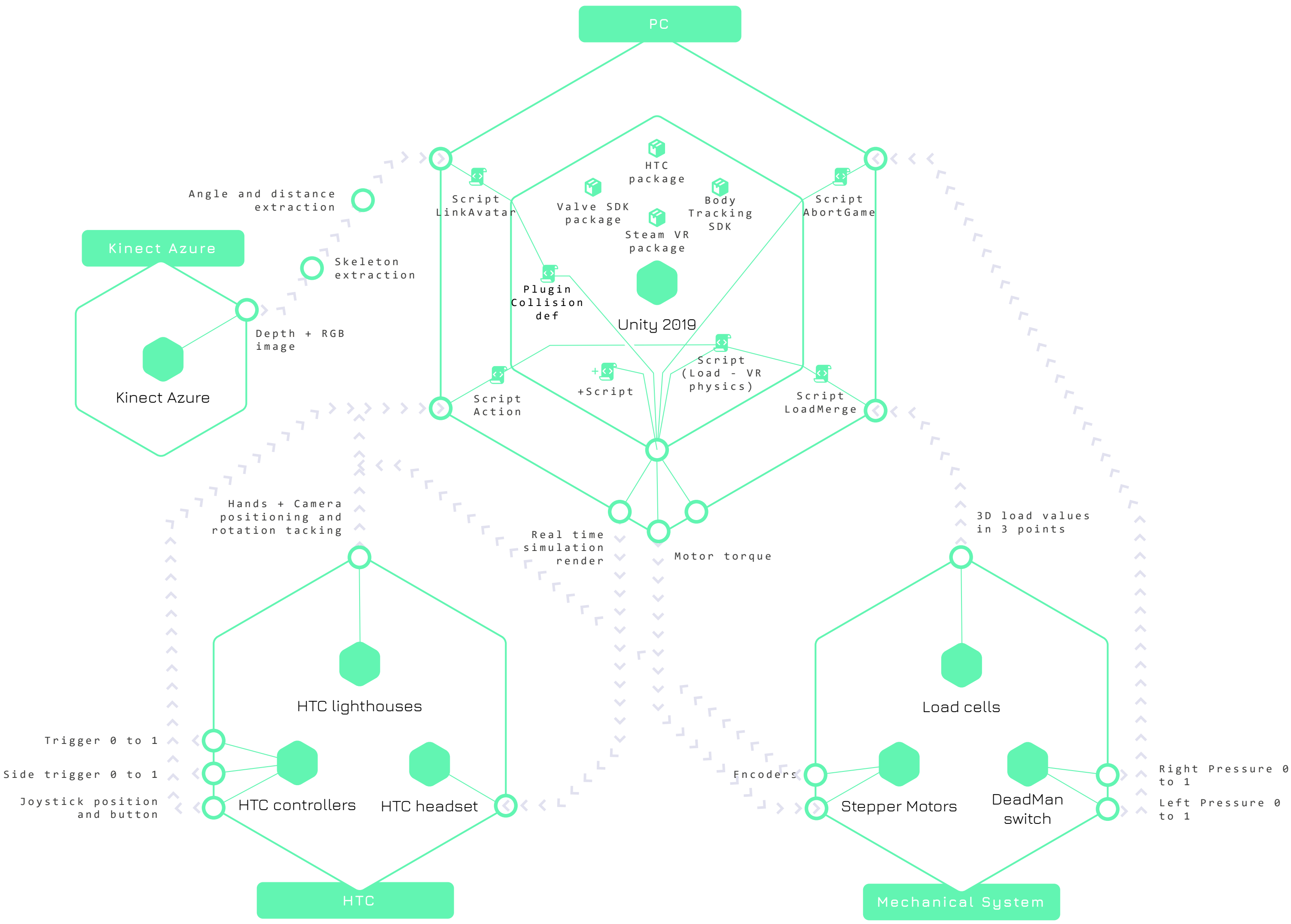


Figure 17.- US prototype's system architecture

2.2 Chapter conclusions

By means of observation and conversations with the client, risks of getting physically injured by the interaction with the Ethereal Engine are detected and subsequently catalogued in **collision**, **posture**, **balance loss** and **long-term exposure**.

From *The Wizard of Oz* experiment, **disorientation** and **loss of real-world reference** when wearing a *VR* headset is observed. Similarly, the **need to adjust** the workout experience to each **user's physical capabilities** is detected. Further research on the parameters that could be used to determine users' capabilities is included in *Section 3.1.3 Posture evaluation and its communication.*

Additionally, the system architecture is presented, emphasising the limitations of each of the subsystems in terms of safety. Among the components, the **dead-man switch** emerges as a solution to escape the experience. Although this mechanism can safeguard a user's physical health against some risks, it **depends on the user's ability to foresee harmful situations**.

Owing to the dynamic nature of these risks, even if the user detects them an instant earlier, getting injured would be inevitable. Furthermore, the dead-man switch disregards the tension generated between an intense workout and the physical safety of the user, simplifying the solution to an active or inactive state and, thus, likely to resulting in **immersion breakdowns**.

Lastly, there are a considerable number of exceptional cases in which the Ethereal Engine might not work well -e.g. multiple people captured by the MoCap resulting in the inability to determine who the user is-. In this context, limiting certain risks emerges as an opportunity to safeguard users' physical health.

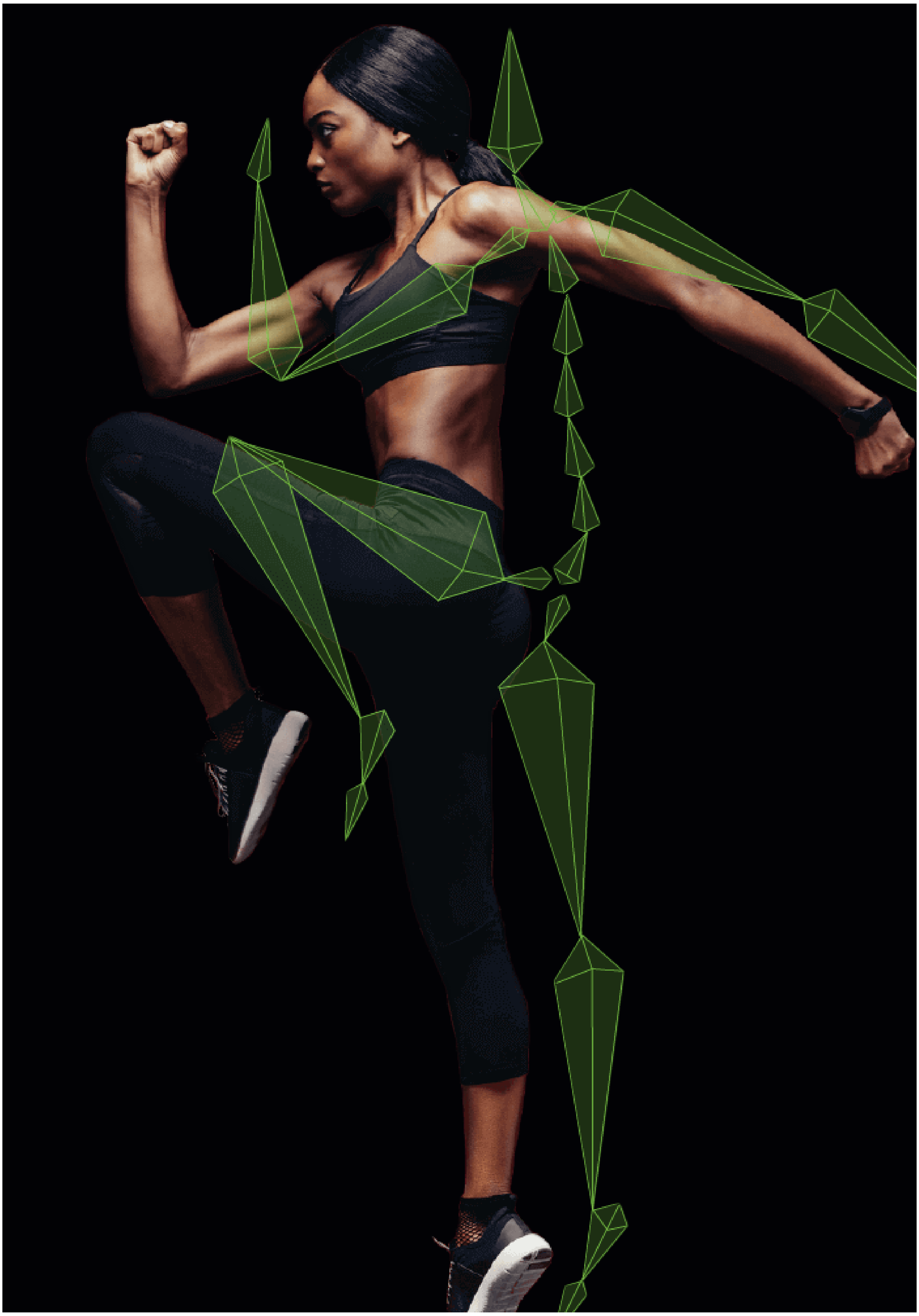


Figure 18.- Yana Motion. Virtual trainer (“The Future of Musculoskeletal Assessments | Yāna Motion,” 2022)

– CHAPTER 3 –

Exploring opportunities

This chapter includes the content relative to the exploration of the most recent advancements in the detection/assessment/reaction systems oriented toward the decrease of bodily injuries.

Additionally, by bringing physical therapist knowledge into play, it elaborates on the qualities that could proportionate an appropriate balance between physical safety and workout effectiveness. Adaptation and communication are underlined, derived from the heterogeneity of body shapes and sizes together with the different patients' needs and ambitions.

3.1 Exploratory research

The content is divided into different sections that aim to provide a fact-based answer to the research questions. These questions dive deeper into the technological opportunities and behaviour during the interaction to successfully provide a bodily injury free workout experience. These are listed below:

i. **What are the up-to-date considerations in the Human-Robot Interaction (HRI) field to reduce the bodily injury risk in the Ethereal Engine?**
ii. **How the Motion Capture data or possibly available data can be used to enhance the Ethereal Engine's safety? And thus, what Motion Capture System should we implement in the Delft Engine?**
iii. **What are the rehabilitation and fitness knowledge/factors needed to define a safer interaction (posture, intensity…)?**
iv. **How do physical therapists behave?**

3.1.1 Human-Robot Interaction

The Ethereal Engine is a machine that inherently involves Human-Robot Interaction -*HRI*-. Schmidtler et al. define *HRI* as *'a general term for all forms of interaction between humans and robots'* (2015). Due to the broad application of the term robot, *HRI* comprehends several areas such as speech communication and natural language processing or physical interaction. This study deepens in a particular category often called physical *HRI* or *pHRI* and aims to explore the up-to-date underlying considerations that can reduce the bodily injury risk of the Ethereal Engine (Vendittelli et al., 2005).

Literature review exploration is performed and complemented with an interview with an expert from the Cognitive Robotics lab of the Technical University of Delft- and their team. (Delft)

During the last decades, the domain of application of robotics has exponentially grown, especially in service robots, encompassing those robots that provide a service for the well-being of human beings. (Guerry, 2020) Although there is no registry of prospects in the Fitness Robot market, within the Medical and Rehabilitation Robotics field, a compound annual growth rate of 25.8% was foreseen in the period from 2020 to 2025 (Mordor Intelligence Llp, 2020). In fact, the appearance of new robot categories, such as collaborative robots or co-robots, has put a spotlight on new safety measures definition. A recent *ISO / TS 15066* standard is spotted by several authors, providing guidance on the collaborative robot safe interaction definition (Matthias & Reisinger, 2022; Scalera & Riedl, 2020). This specification defines four collaborative operation categories which are "*safety-rated monitored stop -SMS-*", "*hand guiding -HG-*", "*speed and separation monitoring -SSM-*" and "*power and force limiting -PFL-*". (Shea, 2016)

With regard to *SSM*, several authors orient the safety of *HRI* towards the minimum distance calculation using body motion tracking (Villani, Pini, Leali, & Secchi, 2018; Secil & Ozkan, 2022). Secil .S et al built a model that from skeletal data acquired with a RGB-D sensor or depth camera created surrounding capsules for user and robot to lastly calculate their relative distance. (2022) As in the Ethereal Engine, B. Whitsell and P. Artemiadis considered the implementation of physical obstacles by having humans and robots to negotiate for a *6DoF KUKA* robot, but decided not to incorporate physical feedback due to the potential of putting the user at a higher injury risk. (2017)

As a *PFL* complementary solution for collision cases, De Santis A. et al. identify compliance, springs, rubber coverings, artificial skin as what they call passive safety solutions, since the behaviour of the robot is not adapted, the mechanical response is tweaked instead. (2008) In fact, until 2011 the maximum force and power exerted by a co-robot were limited by law to 150N and 80 Watts. (Shea, 2016) Additionally, the interviewed experts on robotics recommended the use of torque control over position control to make the robot passively react to human force inputs by limiting the torque.

A last important consideration related to *HRI* is the psychological impact caused on humans because of a physical collaboration with robots. The previously mentioned De Santis A. et al. work reflected on the cognitive fear associated with robots, and how hidden safety devices enhance people's trust on them: ubiquitous systems -e.g. Airbags-. (2008) Besides that, Wenk, N. et al through an experiment conducted on 28 healthy participants with a *VR* headset and a rehabilitation robot realised how visualising or occulting the robot does not affect the interaction in terms of motivation, presence, embodiment, performance, nor visual attention. (2022)

In contrast, Negi S. et al from an experiment run with 21 subjects concluded that "participant leadership and courage is primarily influenced by robot appearance, but little influenced by robot performance". (2008) However, both the last authors noticed a slight increase in trust when robots are visible.

The aforementioned research studies provide relevant insights on the design approach to tackle *pHRI.* Collision risk is considered from afar the most common and studied challenge, generally tackled by using MoCap-based solutions to define the user and robot boundary guaranteeing a minimum relative distance between them. The implementation of a collision detection system in the Ethereal Engine could be pretty straightforward by replicating existing models Other additional safety measures in the physical product, to dampen impacts and restrict user's access to hazardous spots. Apart from that, regarding the physiological features of the *VR HRI*, keeping robots visible in the virtual environments increases the trust slightly. However, visibility might be even more important, since the Ethereal Engine unlike the mentioned robots not only considers upper limb interaction, but also lower extremity. The acknowledgment of the platform edges would increase the trust and potentially the performance, reducing the risk of stepping out of the platforms.

3.1.2 Motion Capture systems and models towards a safer experience

Motion Capture or MoCap offers a way to both enhance the realism of the experience -recreating the user's motion in the *VR* context- and guarantee the physical safety of users -designing skeletal data-based safety mechanisms-. The multiple mocap market solutions raise the question of which system is the most appropriate for the Delft Engine. This study aims to assess what MoCap system should we implement in the Delft Engine to fulfil the aforementioned features.

The following study is a continuation of the analysis performed by the previous team, which resulted in MoCap system implementation proposal and certain requirements covered in the corresponding report -see *Final Review Report, pages 9-10, 14-15-*. The study included in the following pages compliments the previous work, analysing which MoCap technologies would offer a better solution to reduce bodily injuries.

By means of literature review, different Mocap technologies are compared and state-of-art of data models to enhance safety is presented. Furthermore, a MoCap system prototype is mounted on the physical product to gain practical knowledge. Lastly, an interview with an expert on human body digital modelling is performed to assess existing image capturing-based models that could enhance safety.

As stated in the List of Requirements - or LoR- included in *Appendix 2*, the Ethereal Engine's MoCap system has to present minimum intrusiveness. The previous research classified MoCap technologies in three categories: Optical MoCap - or *OMC*-, Inertial MoCap - or *IMC*- and Video-based MoCap - or *VMC*-, which similarly can be divided into marker-based or markerless systems.

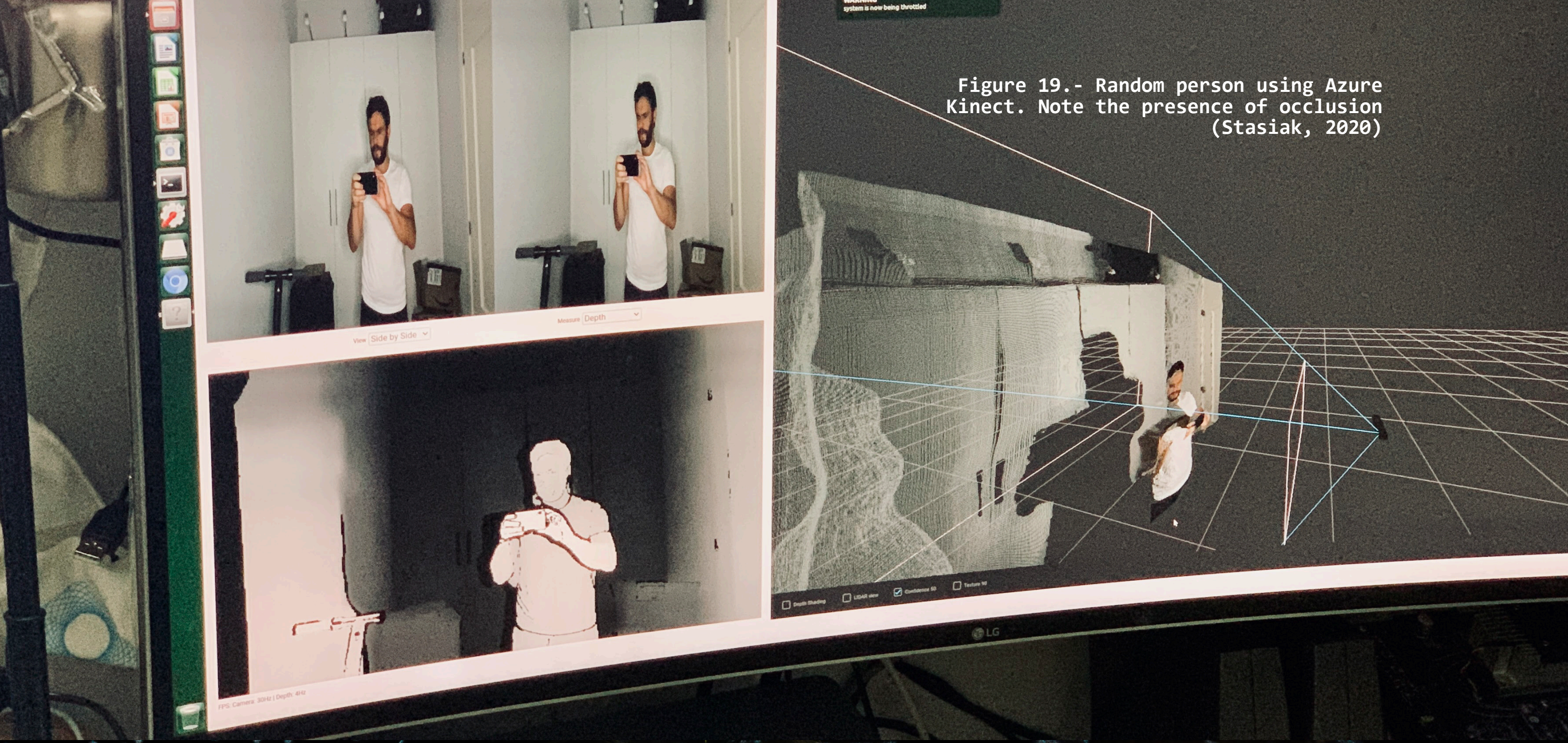


Figure 19.- Random person using Azure Kinect. Note the presence of occlusion (Stasiak, 2020)

Figure 20.- Dancing with Invisible lights. (Penven 2021). Capturing the point cloud emitted by *Kinect Azure*'s IR projector

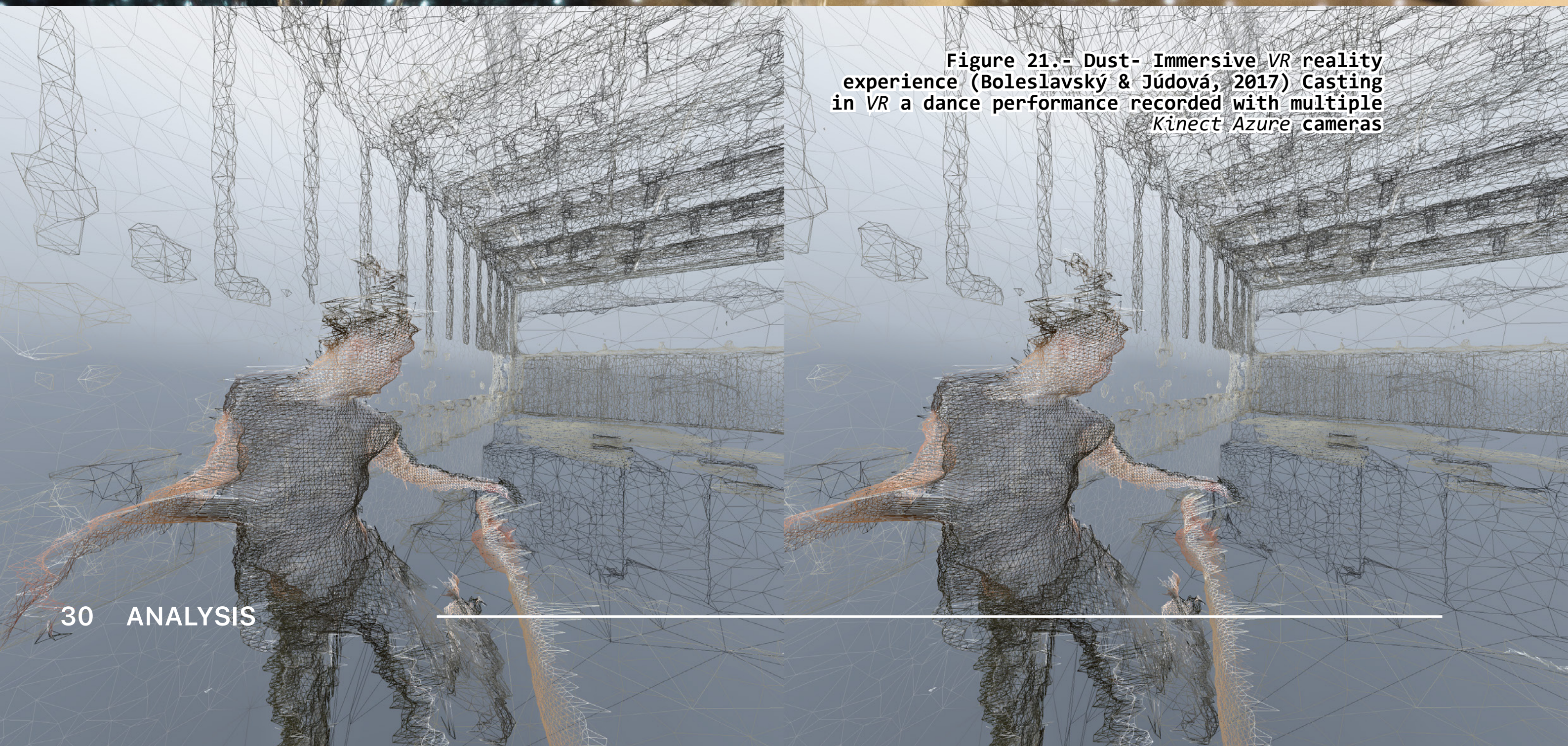


Figure 21.- Dust- Immersive *VR* reality experience (Boleslavský & Júdová, 2017) Casting in *VR* a dance performance recorded with multiple *Kinect Azure* cameras

Marker-based systems rely on wearables with markers that ease the optical recognition in camera-based equipment -as in *OMC*- or even can include inertial measurement units - or *IMU*- providing more accurate skeletal tracking - as in *IMC*-. In contrast to the aforementioned systems, markerless systems comprehend *VMC*, which only consists of one or more video cameras with sufficient frame rate and video processing software. In such a scenario, markerless technologies were prioritised over marker-based due to the lower intrusiveness.

Furthermore, regarding *VMC*, two main approaches are distinguished: depth-camera-based and deep-learning-based -see *Figures 22* and *23*- (Nakano et al., 2020)- From these two technologies, different hardware/software solutions were discussed taking into account latency, performance in different lightning conditions, occlusion, and cost.

Depth-cameras or *RGB-D* sensors, are based on time of flight measurement, which lies in projecting a point cloud over a 3D space and recording the time between the release and return of each light beam - e.g. *Kinect Azure* , see *Figure 20*- ("*Azure Kinect DK hardware specifications | Microsoft Docs*," 2021). By means of this technology an accurate 3D volumetric representation of the user is acquired, disregarding occlusion -see *Figures 19 & 21*-. Apart from *Kinect Azure*, the *StereoLabs ZED 2* camera is spotted as counterpart product. (*Stereolabs3D*, n.d.)

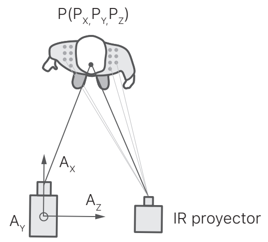


Figure 22.- *VMC*- Depth camera -*Kinect Azure*-

Deep-learning models instead, are based on computer image processing for pattern recognition - e.g. *Openpose*-(Nakano et al., 2020). As in other computer vision applications, the performance is conditioned by the amount of training data available. In fact, these systems are biased due to their statistical inception. For example, detecting infrequent and hardly predictable body configurations, such as the belly of a pregnant woman, is challenging. Some Deep-learning-based MoCap softwares are *MoCapForAll, Captury, Deepmotion* and *Optitrack Motive, MoSh, XNect* (under development).

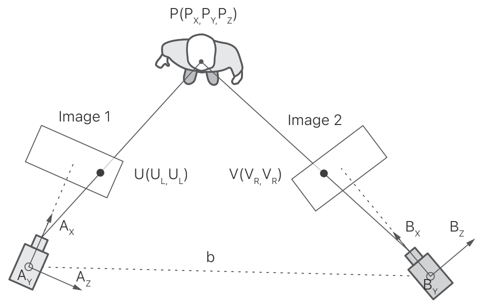


Figure 23.- *VMC*- Deep learning-based triangulation

As the main disadvantage of depth-camera-based MoCap systems, solving occlusion comes at a higher cost, considering the price of the hardware -from 300 to 500€-(MicrosoftStore, n.d.; Stereolabs3D, n.d.). In this scenario, Inverse Kinematics emerges as an alternative mathematical calculation to locate intermediate occluded nodes -e.g. elbows or knees- according to physiologically possible postures -*see Figure 24*-. This technique is commonly used in *VR* games, such as *Population One*, where elbow position is estimated from controllers and headset relative position ("*POPULATION: ONE - Battle Royale in VR*," n.d.). However, from a safety perspective, the resulting elbow position is one of the multiple different combinations and does not provide a reliable representation.

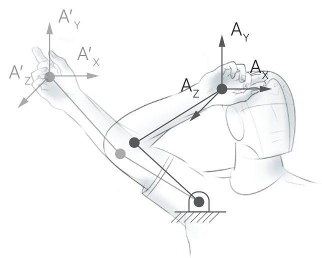


Figure 24.- Inverse Kinematics for elbow positioning

Since most of the body tracking techniques result in multiple nodes location in the 3D space, we could ask ourselves: how can we digitally obtain an accurate volumetric human geometry? There might not be a single answer for this question. Using depth cameras the contour of the subject could be directly used to create a boundary. For example, Wang K. et al created a model which reconstructed a 3D human body model from noisy depth data combining skeletal and mesh deformation information (2020). In contrast, Black M.J. et al. developed a software -*MoSh*- to replace the skeleton data acquired by means of OMC equipment with a 3D parametric model, converging in what they call Dynamic MultiPerson Linear -DMPL- model, which not only estimates body shape but also simulates dynamic tissue deformation -see *Figure 25*- (2014). Additionally, the DINED project from the TU Delft offers a tool to generate 3D models based on anthropometric measurements and other data such as weight and sex (Molenbroek, 2018). By conversing with the DINED 3D/4D Anthropometry Leader, the possibility of linking these 3D models to skeletal structures using Mixamo is detected ("*Mixamo*," nd.).

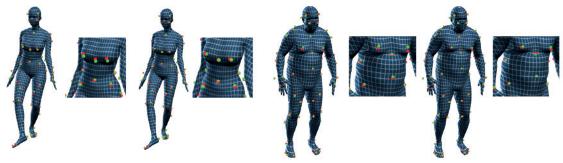


Figure 25.- Mosh Soft Tissue Deformation. *"Green balls correspond to the mocap markers. Red balls correspond to the simulated marker locations."* **(Loper, Mahmood, & Black, 2014a)**

Reflecting on the applicability of aforementioned MoCap technologies to the Ethereal Engine, depth cameras offer better accuracy at a higher cost, however multi RGB camera-based systems provide a low-cost solution that overcomes occlusion. Considering the different benefits that both systems offer and the continuous development of systems with better features, both systems are considered as relevant paths to pursue. Additionally, digital human modelling is understood as an opportunity to improve presence and safety - letting users be aware in *VR* of their physical constraints-.

3.1.3 Posture evaluation and its communication

During the last few years, several fitness service initiatives revolving around the digitalisation of fitness coaching, also known as virtual trainers, have emerged (Health, n.d.; Kinetisense, n.d.; VAY, n.d.). The majority of these service suppliers make use of deep-learning-based *VMC* for such purposes as counting repetitions, providing feedback on posture and recommending fitness plans, among others -See *Figure 27*-. This section aims to explore how these solutions work, laying special emphasis on the desired communication and behaviour to keep the experience both engaging and safe.

In this study, state-of-art and challenges in pose detection and evaluation for the fitness and rehabilitation areas are explored. Lastly, an interview with a physical therapist is conducted to shed light on how these professionals face a rehabilitation process -from pain assessment to physical interaction- . Topics as how they behave to correct bad posture and have a positive impact on the patient's recovery habits are discussed.

A big part of these virtual trainers are user-friendly smart-phone applications that do not require any additional equipment than an optical camera covering the workout zone. These solutions integrate a 2D real-time pose detection model combined with training feedback (Health, n.d.; Onyx, n.d.). They are inexpensive, however, they present difficulties identifying certain postures, and are bad at dealing with occlusion. For professional training purposes, systems based on multiple cameras or *RGBd* sensors are used, where data is post-processed and analysed by experts instead of doing it computationally (Kinetisense, n.d.). Kinetisense is an example of that technology and proposes 4 different modules that provide users with insight on how to improve balance, posture, functional movement and range of motion through a user-friendly graphical interface -see *Figure 26*-.

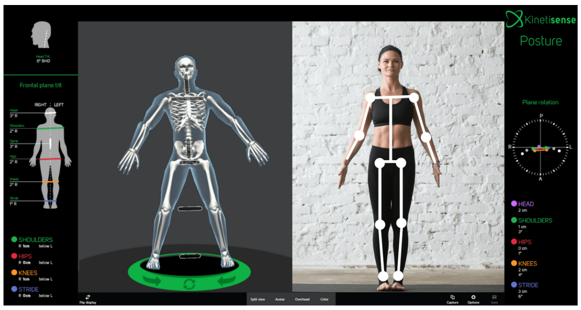


Figure 26.- Kinetisense UI (Oppfamilychiropractic.com, 2019)

Concerning the aforementioned pose detection models, Hachaj, T., et al developed a gym activities classifier using MoCap data applying neural networks. (2016) Örücü, S. and Selek, M. developed a rules-based model for defining a correct LR -Lateral Raise- and DSP -Dumbbell Shoulder Press- using skeletal data. The rules were based in consultations with Physical Education and Sports Teaching experts and a certified

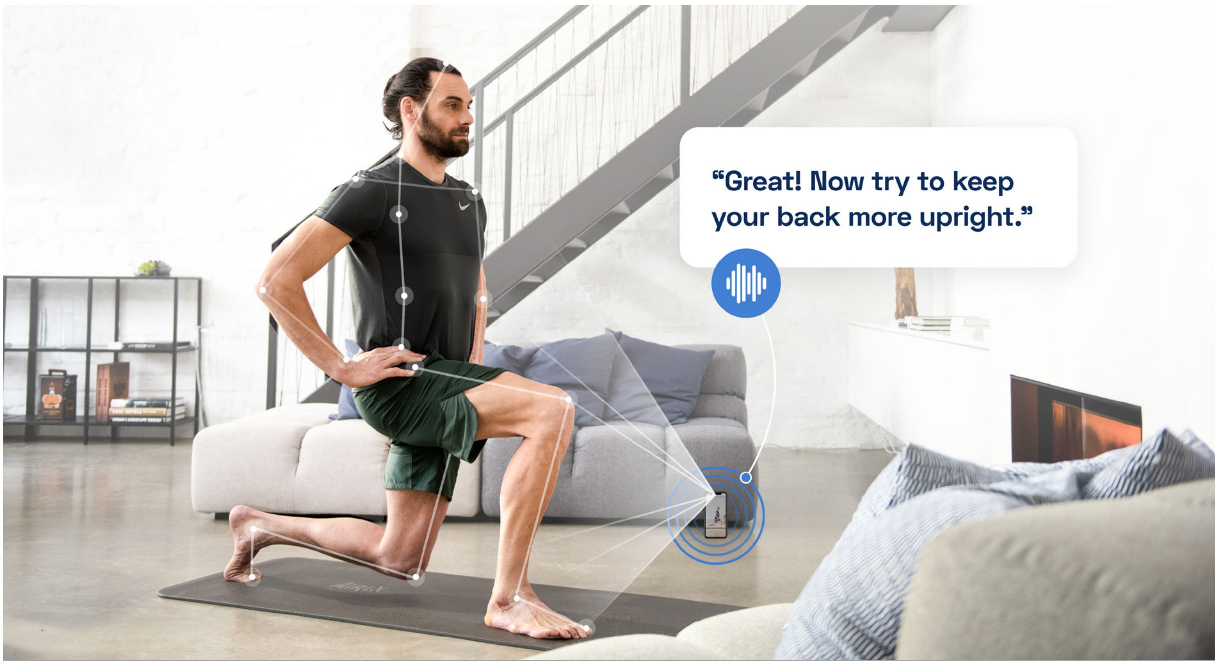


Figure 27.- Kaia Health. Virtual trainer (Kaia Health, 2020)

trainer. (2020)
The efficacy of virtual trainers depends both on an accurate MoCap system and a deep knowledge on the body kinematics. Regarding this last need, Milanko, S. and Jain, S. identify a list of barriers hindering effective virtual trainers development. (2020) These are "*the lack of standard guidelines for form and motion, the lack of standard performance measurements, the diverse individual style of weight lifting and the limited and subtle body motion*".

Besides that, Lang. C. et al developed an accelerometer data-based method to quantify upper limb performance and reported kinematic asymmetry between the dominant and non-dominant arms. (2017) Similarly, Jee H. and Park J. detected more controlled movements in the dominant sides during abduction and adduction lateral raise motions. (2019)

After getting a better understanding of the capabilities of virtual trainer solutions, an interview with a physical therapist is performed to deepen on how they behave to keep patients engaged during a rehabilitation process and how we could design games that would avoid harmful postures.

Before diving deep into the insights, it is worth it taking a look at the rehabilitation process. *Figure 28* includes a schematic process flow which includes a sequence of the actions that take place in the first patient - therapist interaction.

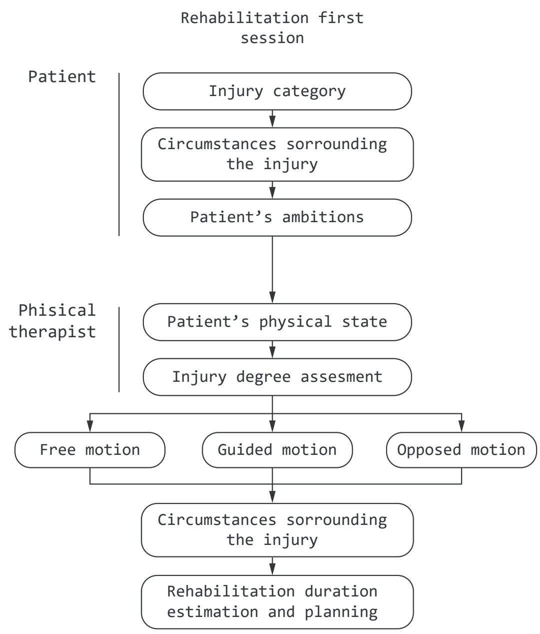


Figure 28.- Rehabilitation. First session procedure diagram

One of the most relevant insights obtained, is related to the method they follow to overcome the lack of knowledge on the scale of injury of new patients. Since not only every injury is different, but also the way we people perceive pain, pain scales are used to assess the tolerance of the patient to certain movements. These movements can be either free, guided or blocked by the therapist. The therapist acts as a highly sensitive system able to measure force and exert a response according to the exercise's purpose.

Normally rehabilitation progress is measured by self comparison with previous personal records and similar populations -see *Figure 29*-. They highlighted the importance of shared decision-making and of mentioning the activities plan before starting the session to avoid patients getting surprised. Occasionally, to deal with patients who doubt the process, he offers them information about the activities and their direct benefits. Honesty is spotted as the most valuable feature expected by physical therapists from patients.

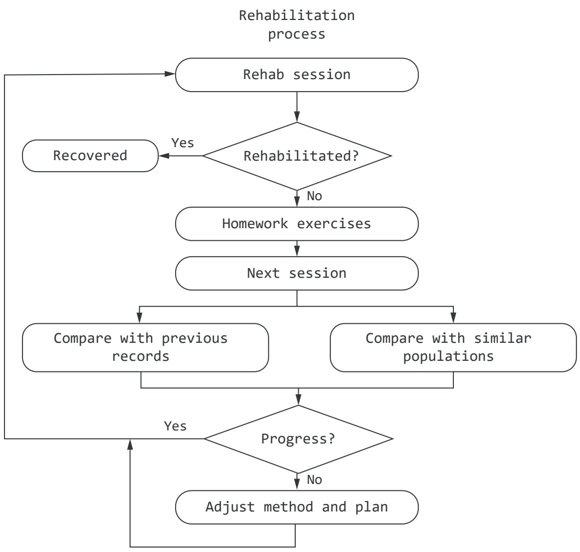


Figure 29.- Rehabilitation. Process diagram

With regard to the assessment of current games, unsynchronised movements are frequent in gym exercises, but equipment-wise there are not so usual. Unfortunately, there are no universal guidelines in terms of human motion correctness for neither rehabilitation nor fitness, except for the traditional Russian strength gymnastic methods that are just applicable to exceptional athletes. Additionally, they spotted as essential factors that influence the training experience: frequency, load, duration, and recovery times that are dependent on age, sex, physical state, previous activity during the day.
Lastly, as a strategy to create a long-lasting experience, training different muscle groups and setting recovery times are identified as necessary to rebuild energy for the next set.

Thanks to the aforementioned research, factors affecting the workout are detected: age, sex, physical fitness and previous activity. Similarly, factors that can be used to adjust the workout are spotted: frequency, load, duration, recovery time. In this context, calibration processes to adjust and personalise the workout experience are spotted as a promising feature to incorporate to the Ethereal Engine. Besides that, by offering information to help users trust the process - e.g. to achieve their fitness goals- the perception of the machine could be improved.

As a last remark, the lack of standard guidelines emerges as a difficulty to prove the correctness of exercises. Additionally, when exercising certain postures tend to be demonized, even though every human being due to its unique body constitution needs to adopt a certain posture. For example, looking at squats every person requires a certain distance between feet to properly complete the downwards movement while keeping the ankle on the floor and an appropriate back posture. However, this knowledge gap can be overcome with side-to-side collaboration with sports sciences experts -physical therapists, personal trainers, etc.- to stablish certain laws of minimum combined with flexible machine learning models that could learn the user's postural needs.

3.2 Chapter conclusions

Broadening the knowledge on safety, mechatronics, motion capture technologies and physical therapy, a holistic comprehension of the interacting disciplines that the EE brings together is obtained.

According to literature, **collision detection** plays a big part in the safety mechanisms definition in the *pHRI* field, where **depth-*RGB* sensors** emerge as the most widespread solution. As an alternative approach, **multi *RGB* camera** solutions offer a solution to considerably reduce the cost, eliminating occlusion, but presenting the limitations of *ML*-based models -mismatch for exceptional cases, e.g. a pregnant woman-. In addition, **body shape modelling using MoCap** emerges as a potential opportunity to reduce the mismatch, adjusting the avatar to the user's body size.

From a mechanical design perspective, the mechatronic experts reached **doubt on the position control approach** user in the EE, since normally for robots involving *pHRI* torque control is used.

In addition, the psychological aspects related to including robots and *VR* in fitness are explored. Due to the limited information on gymnastics, *VR* in rehabilitation is used as a reference. The discussed literature calls attention to the controversy of how visualising or occulting the robot affects the interaction. However, these sources agreed upon the fact that the **trust in the robot slightly increases when visible in** *VR*.

Furthermore, **virtual training solutions happen to be in their boom**. **User-friendly apps** that use one camera-based computer vision to track the user's motion are **inexpensive solutions**. At the same time, **solutions for professional athletes** are developed where postural data is collected by machines and post-processed by real experts. However, the engagement of both these solutions is remarkably low due to the limited feedback.

From an interview with a physical therapist, how these experts tackle the rehabilitation process is consulted. The **adaptation to user's needs and ambitions** together with the **communication of rehabilitation sessions** to let users exercise accordingly are considered relevant features for successfully incorporating a virtual trainer in the Ethereal Engine. Furthermore, it is understood that the **lack of guidelines** derives from the **heterogeneity of body shapes and motions**, however this gap is normally overcome by comparing with similar populations. Factors to configure the rehabilitation session and tips for increasing the engagement of patients that do not trust the process are gathered, but these last vary depending on the user's ambition and nature. These factors are **frequency, load, duration, and recovery times** that are dependent on **age, sex, physical fitness, and previous activity during the day**.

The conducted exploration not only resulted in insights for creating a meaningful design but also shed light on the current knowledge gaps. These are identified as potential research opportunities for further development of the Ethereal Engine. For the time being, the mechatronic systems which provide high-force physical feedback for *VR* fitness are quite limited. In fact, it is still an open question what the general limitations of using robotics in *VR* fitness are -considering demanding force feedback- and if the requirements could be extrapolated from disciplines such as rehabilitation until the creation of specialised standards.

Similarly, being the virtual trainer concept still in its infancy, the Ethereal Engine would provide an **additional feedback** mechanism to further develop user-robot communication: apart from the common visual or auditory ones, the possibility of adjusting **force** to communicate an intention. As a last consideration, the limited knowledge of robot interaction and adaptability when a user rejects recommendations arise as complex challenges to be tackled by designers, in collaboration with physical therapists and game developers.

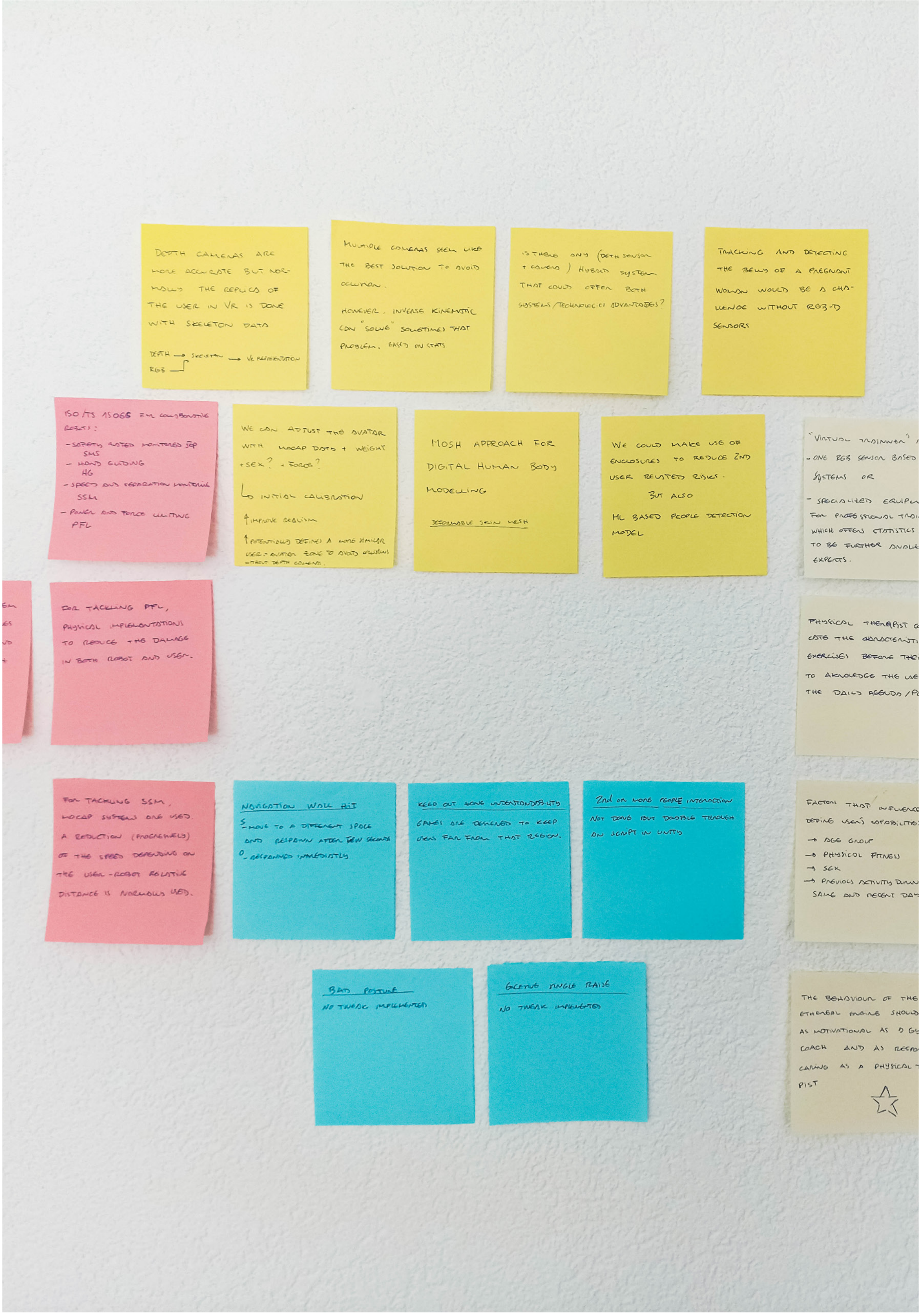


Figure 30.- Map of insights obtained from the research activities

- C H A P T E R 4 -

Synthesizing towards a challenge

This chapter includes the necessary decisions to understand the design intervention. From this chapter on the nature of the presented content tends to acquire a more evaluative approach, rather than informative.

Initially, a discussion of the main research insights is included, followed by an adjusted version of List of Requirements -or *LoR*- integrating the knowledge obtained during this Graduation project. Thanks to the aforementioned discussion and *LoR*, posture evaluation is selected as the challenge with a differential potential over the rest to bring Ethereal Engine to the next level, providing an experience in which bodily injury risks could be reduced, motivating the user to adopt better postural habits when working out. Lastly, a design vision is formulated for the spotted risk, emphasizing the need for inspiring users to self-correct their posture instead of imposing rules in order to avoid possible immersion breakages.

4.1 Introduction

As in every project, no matter the discipline, the phase of synthesis towards a solution proposal comprehends a digestion of a ridiculous amount of knowledge. Hence, normally as engineers, we make use of tools as Lists of Requirements and Design Visions -these last especially in design projects-, among others, to guarantee that the information is preserved and fruitfully integrated into a product.

Translating this reflection into this project, the injury risk exploration included in *Section 2.1.1 Injury risks exploration, understanding machine's limitations* resulted in multiple challenges that should be somehow tuned to let the Ethereal Engine be a successful product. However, although all those challenges are spotted as elements for improvement, the interdisciplinary conversations performed during this research -e.g., mechatronics, physical therapy, digital human modelling experts- shed light on the state of art of each of them and help select a promising development path.

Said so, the main drivers derived from the research are listed below:

- Being the knowledge of physical therapists incorporated for the first time in the Ethereal Engine's development, it is learnt that seeking universal guidelines that could ease the definition of correct postures and motions is not a smart choice. Since every person due to his body constitution requires a unique posture, these guidelines would be biased according to the population that runs the tests.

- In this scenario, *ML* could be targeted as a promising tool to overcome the need of calibrating the experience for each user. Supervised or Unsupervised *ML* models are suboptimal since they do not incorporate user data and feedback. Reinforced *ML* instead emerges as the most promising alternative since these models can continuously learn as the user exercises in the engine. Considering 45 minutes as the common duration of a fitness session, the machine could recommend occasional calibration sessions where it would compile postural data and adjust the experience.

- Collision-related risks are widely researched in mechatronics. In other words, there are multiple models/solutions that an expert could adjust guaranteeing no collision risks. Gradual incrementation of the resistance as collision risk increases is proposed to tackle this challenge, together with an alteration of the *VR* interface to get the risk across.

- There is not a clear answer for the selection of a Motion Capture technology. ML-based multi-camera MoCap solutions are emerging as low-cost solutions to improve occlusion. These can track complex postures -e.g., arms or legs crossed- more accurately, however cannot create a boundary surrounding the user as in depth-cameras.

4.2 List of Requirements

The following requirements complement the Joint Interdisciplinary Team's work -see *Appendix 2-*, further elaborating on the features of the virtual experience to reduce the bodily injury risk while keeping the experience engaging.

Table 1.- Requirements derived from the conducted research

ID. Code	Name	Description	Measurement Criteria
UX-003	Minimum intrusiveness of the MoCap system	Provide a minimum intrusiveness.	-Short or null set up time, letting the user start the experience without previous preparation. Less than 1 minute. -To be ready for multiple uses, directly one after the other.
UX-005	No occlusion	Overcome occlusion making use of the current techniques available. •Multi Camera systems •Inverse Kinematics •Other ML based computational models	Play zone fully covered. (1.8m x 1.8m x 2.3m)
UX-010	Replication of the user in the *VR* context	Track the user posture as accurately as possible for the current games. Handstand positions are out of the scope.	Min Accuracy 1-5 cm Frame rate 30 to 60fps
UX-011	Acknowledgement of the required movements to play games	Games need to be understandable, so as users relate certain movements of the controllers to the intended activity of the game.	User testing. Acceptable score: 8/10
UX-012	Adjustment of the virtual training to the user characteristics	Adapt the exercise to the user capabilities. For example, in the ornithopter game a certain user that exercises shoulders on a regular basis could lift repeatedly more load than another user that does not frequent gyms so often.	Different users with different bodies can obtain same scores in terms of gaming.
UX-013	Planning of the exercise session	Communicate the physical demand of the game beforehand to work out.	User testing. Acceptable score: 8/10
SF-003	Human - robot collision avoidance	Keep a minimum relative distance between its respective components and the human body.	Min distance -end effector: 10 cm Min distance -intermediate parts: 10cm Assess hetereogeneous body shapes: e.g. Pregnant women belly
SF-004	Robot - robot collision avoidance	Keep a minimum relative distance between its left and right armatures not to get damaged.	Limited to centre or unlimited consider-ing a min. distance : 10 cm.
SF-005	Bystander - robot and bystander -human collision avoidance	Include a system to keep track of bystanders that suppose a collision risk.	No risk to injure bystanders in different scenarios.
SF-006	Robot -human interaction close to the keep out zone	Physical-mechanical limitations of the robot generate an unreachable zone. An attempt to reach this zone would result in a sudden stop injuring the user and damaging the system. Current games opt for enabling activities far from that zone, however in a close future this feature would be valuable to add flexibility regarding the motion options.	Min distance: 5 cm from the mechanical limit. Gradual incrementation of motor torque when getting close to the keep out zone.
SF-007	Acknowledgement of the keep-out zone	Communicate the keep out zone limitation letting users understand the risk of getting injured or damaging the system.	User testing. Acceptable score: 8/10
SF-008	Real-time bodily injury avoidance due to a repeated bad posture	Lifting weight leaning the back forwards is a clear example of common bad posture habits deriving in back pain in the long term.	User testing. Acceptable score: 8/10
SF-009	Cybersickness risk reduction	Cybersickness is a term that includes loss of spatial awareness, nausea, dizziness, disorientation, caused by: • Apparent movement. Headset latency and FoV. • Realism of the *VR* environment. • Mismatch when user's motion do not correspond to simulated one.	User testing. Acceptable score: 8/10
SF-010	Fainting detection	Detection of fainting to communicate the emergency.	Heart rate and other user state tracking sensors working

4.3 Challenge selection

Once the main drivers have been discussed and the *LoR* has been updated, a convergent procedure towards the selection of an individual bodily injury risk takes place.

Figures 31-35 include a visual overview of the identified challenges, complemented with initial ideas on detection and actuation systems. As it can be observed in the *LoR*, all challenges are somehow included as part of the requirements that the Ethereal Engine should fulfil. However, there is not a unique solution that would resolve all these issues.

In this context, it could be asked how some risks are ruled out. Although all challenges are considered beneficial for the development of the Ethereal Engine, some of them exhibit features or conflicts that could differentiate the engine from its market competitors.

Therefore, the design of a virtual trainer that could facilitate the maintenance of a correct posture while exercising is spotted as the most promising feature to continue with. It grants the designer the opportunity to explore how users could be oriented towards better postures without forcing them. This situation needs

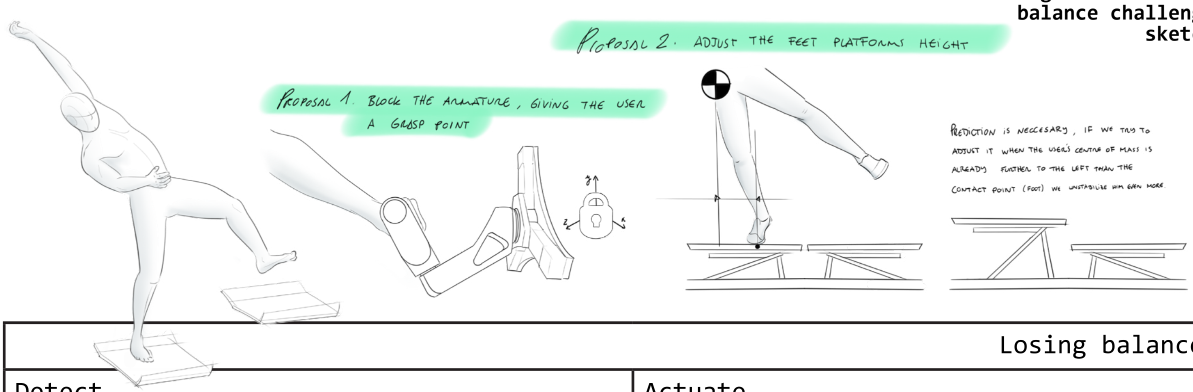


Figure 31.-Losing balance challenge sketch

	Losing balance
Detect	Actuate
Detects the centre of gravity of the user displaced from the contact point with the platforms using -MoCap -Force-torque sensors in the platforms	- Lock the hand grips to give users a grasp point. - Include Airbags

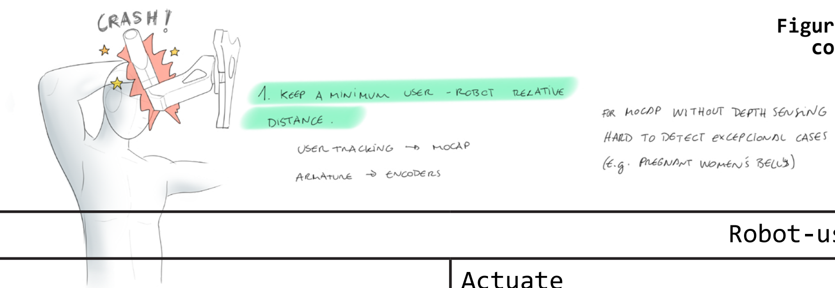


Figure 32.- Robot-user collision challenge sketch

	Robot-user collision
Detect	Actuate
Detect user position with MoCap and end effector with encoders and *IMU*.	Define a minimum safety distance and augment the opposition when getting close to that boundary simulating a damper effect.

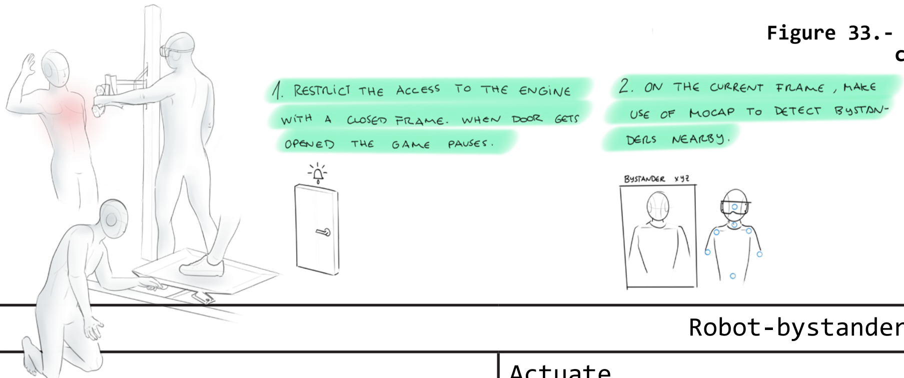


Figure 33.- Robot-bystander challenge sketch

	Robot-bystanders collision
Detect	**Actuate**
- Build a closed frame and place a sensor on the door to detect open/closed -Run MoCap with multiple user detection and/or tracking	- Stop the experience, setting the controls in free motion -Stop the experience, gradually increasing the opposition of the controls until they are blocked.

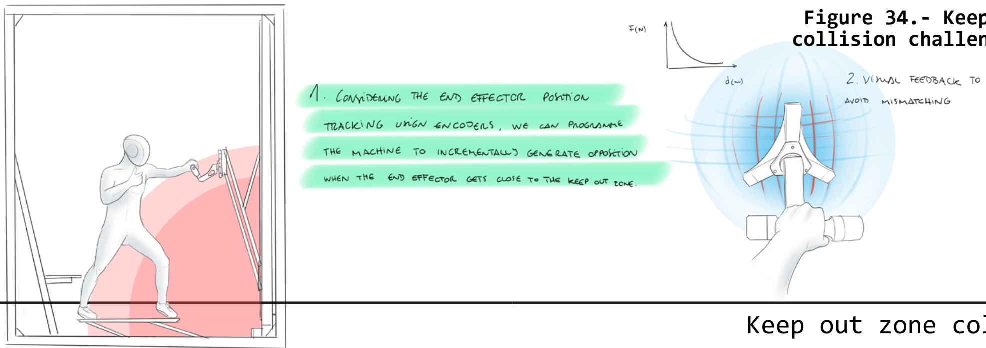


Figure 34.- Keep out zone collision challenge sketch

	Keep out zone collision
Detect	**Actuate**
Make use of the encoders to get the end effector position	Augment the opposition when getting close to that boundary simulating a damper effect.

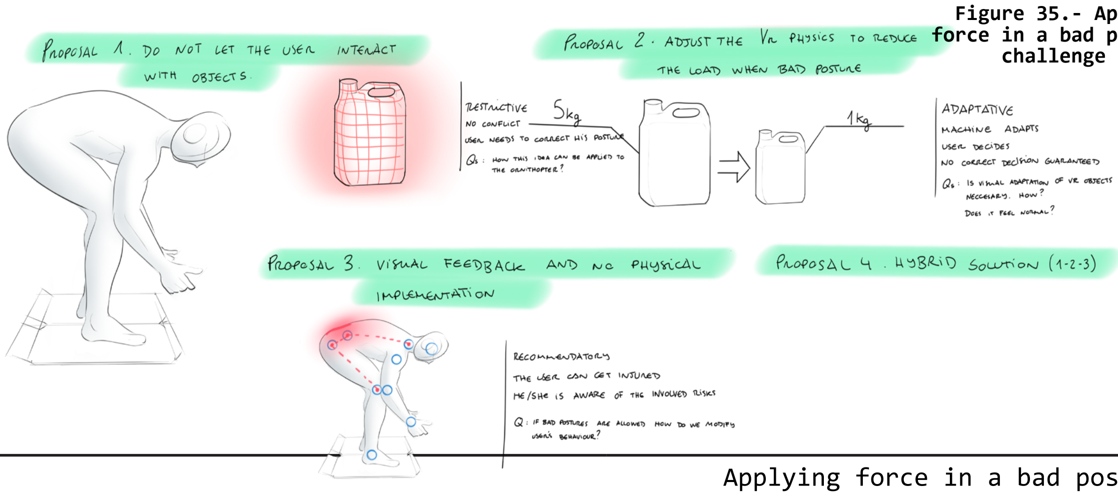


Figure 35.- Applying force in a bad posture challenge sketch

	Applying force in a bad posture
Detect	**Actuate**
Use MoCap to detect user posture	- Reduce the opposition when bad posture - Visual feedback to acknowledge the user how to correct his posture

from users' collaboration to be corrected, in contrast to collision-related risks, where the Ethereal Engine by means of certain coded rules could fully avoid crashes. Furthermore, virtual trainers are in their boom, and Ethereal Matter could take an active part in their development considering force feedback inputs.

The decision of not taking balance loss as the challenge to explore derives from the opportunity to simply reduce their frequency by conditioning certain postures. Thereby, the implementation of a virtual trainer system that provides postural assessment and guarantees the physical safety of the users is taken as challenge to further develop.

4.4 Design Vision

Together with the main drivers and the decision of developing an engaging posture correction system, the design vision further describes the values this design implementation wants to evoke.

"*Inspire*" is understood as a relevant word in terms of behaviour the machine should address. Being a virtual trainer a system that constantly analyses your performance, the way is implemented plays a critical role in order to avoid users feeling constantly criticised. Imposing certain behaviours could lead to rejection by some users, reducing the engagement of the engine. Both "*safety*" and "*comfort*" play as well an important part not only in relation to actually reducing risks and overwhelming situations but also in enhancing the user's perception on these matters.

I want the user to experience the adrenaline rush of the Ethereal Engine while providing at a deeper level the safety and comfort inspired by a physical therapist. The safety I am trying to address wants to inspire the user to self-correct their posture in the long term, without limiting the fun.

4.5 Challenge description

This section includes a brief description on the reflection towards the concepts. Mind maps, sketching, rapid prototyping and a creativity session with gaming experts are the conducted activities for designing a virtual tool for postural assessment. For simplifying the operational functioning of virtual trainers, a simple initial scheme of the system architecture is presented. This comprehends 3 main stages: detection / assessment / feedback.

4.5.1 Detection

The posture detection comprehends mostly the technical aspects, and is primarily related to MoCap. The technological opportunities are depth-based RGB cameras or multiple *RGB* cameras. Since both systems potentially will lead to an effective system, a continuist development to the *JIP* team is performed using multiple *RGB* cameras and *MoCapForAll*.

Additionally, a simultaneous reflection on whether the user should be aware of the positional tracking or not is performed. For this purpose, an initial stage of calibration when accessing the EE is targeted as a potential opportunity to engagingly inform the user about the system's features. The user would be guided through a calibration process including the following steps:

- Put the feet centred in the feet platforms
- Extend your arms laterally
- Wait until the calibration is completed. This process adjusts the avatar's body to the user's shape and it is used to make an initial configuration of the physical capabilities of the user.

As an alternative idea:
The aforementioned calibration process could be run in the background just with a simple text -e.g. "calibration in progress"-.

4.5.2 Assessment

For the postural assessment, the options available are rule and *ML*-based models. Rule-based models present no flexibility in the long term. Prediction models based on machine learning algorithms, in contrast, allow the system to adapt to each user, in such a way that if the user presents any terminal injury and needs to adjust the behaviour. However, for an initial *MVP* -minimum viable product- a rule-based system could show off the functionality and retrieve postural data to subsequently update the model using a *ML* algorithm.

Note that to successfully implement these models, a solution to mitigate the noise derived from the MoCap system's measurement inconsistencies should be applied. Indeed, current MoCap data should not be taken as a 100% trustworthy technology since it is subjected to deviations when complex postures are presented.

4.5.3 Feedback

The selection of information to be transmitted to the user and the way it is done plays a fundamental part in the success of the user interaction. Said that, robots need to send information able to be received by human sensory channels (sight, hearing, taste, smell and touch). Most common feedback options are the visual and auditory ones; however, the Ethereal Engine enables hands and feet force sensing as new feedback opportunities.

Down below you can find a clarifying example of the importance of an effective communication,

For the last few months I had the opportunity to experiment with an Oculus VR headset, regularly playing a mainstream VR game called BeatSaber. Leaving aside the amazing fun it provides, the purpose of the game is to cut floating cubes following a specific direction with your lightsaber. One of those days, I managed to complete a level cutting all blocks correctly. However, to my surprise, I did not get the maximum score. Being intrigued, I googled and I found some rules that could help me to get the extra points.

The main takeaway from the previous story is that even one of the most popular games in *VR* lacks certain communication details that can irritate the user. Luckily in such a mainstream game, some *Youtubers* enlightened me on the tips to get higher scores.

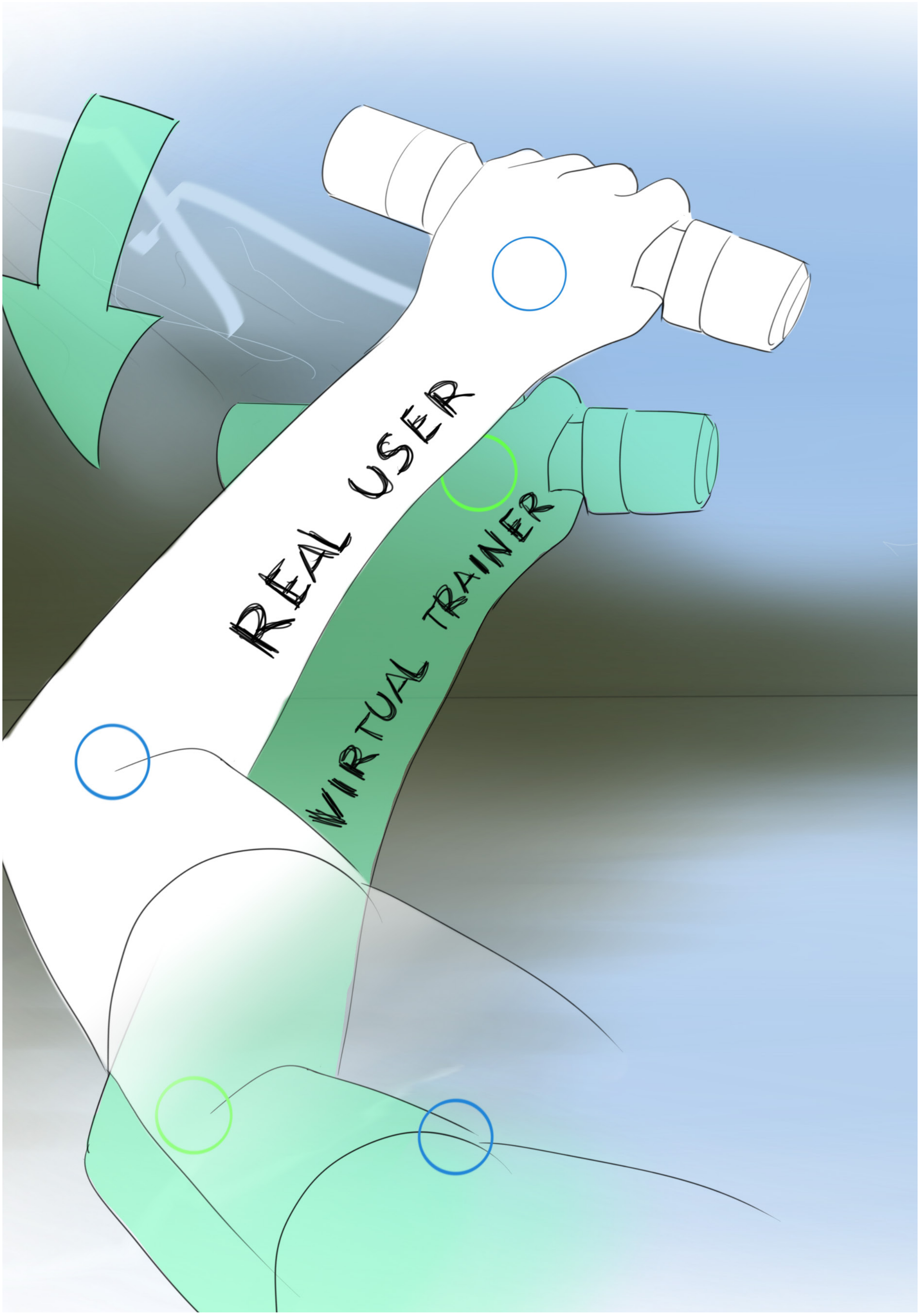


Figure 36.- Virtual trainer as a ghost that guides users to perform certain moves

- C H A P T E R 5 -

Concept design

In this chapter, three concepts are proposed and afterwards discussed, spotting certain qualities -strictness, explicitness, immediacy of the feedback- as parameters that require to be tuned to incorporate an engaging and safe virtual trainer in the Ethereal Engine.

In addition, the envisioned interaction is explained, providing the reader with a holistic perspective of the user journey from the access to the exit of the platform. And at the same time, explaining where the proposed concepts would incorporate changes into the current interaction journey.

5.1 Concepts

During the conceptualization phase, one of the concerns that arose was how to lead to correct postures without resulting in boring or too constricting. In this context, a consultation with two game developers based in Madrid was conducted to co-create possible feedback solutions that would motivate the user to correct their posture and evaluate different concept solutions.

This consultation or creative session was structured in the following way. First, by means of storytelling, an idyllic scenario was presented disregarding any risk that the Ethereal Engine entails. Afterwards, once the participants were aware of the capabilities of the engine, the example of a user getting injured due to the adoption of a bad posture was explained. Finally, questions related to how users' decisions are influenced in the gaming world were asked.

Among the most relevant ideas, they mentioned the possibility of including the concept of "rewards and punishments" as a solution to foster correct postures while exercising. In other words, the performance in the game could be influenced by the users' posture inspiring the user to avoid injuries derived from bad posture.

Likewise, they noted the importance of including tutorials in which each control action is repeated at least 3 times to communicate user's the purpose and controls of each game.

In the following pages three concepts are presented.

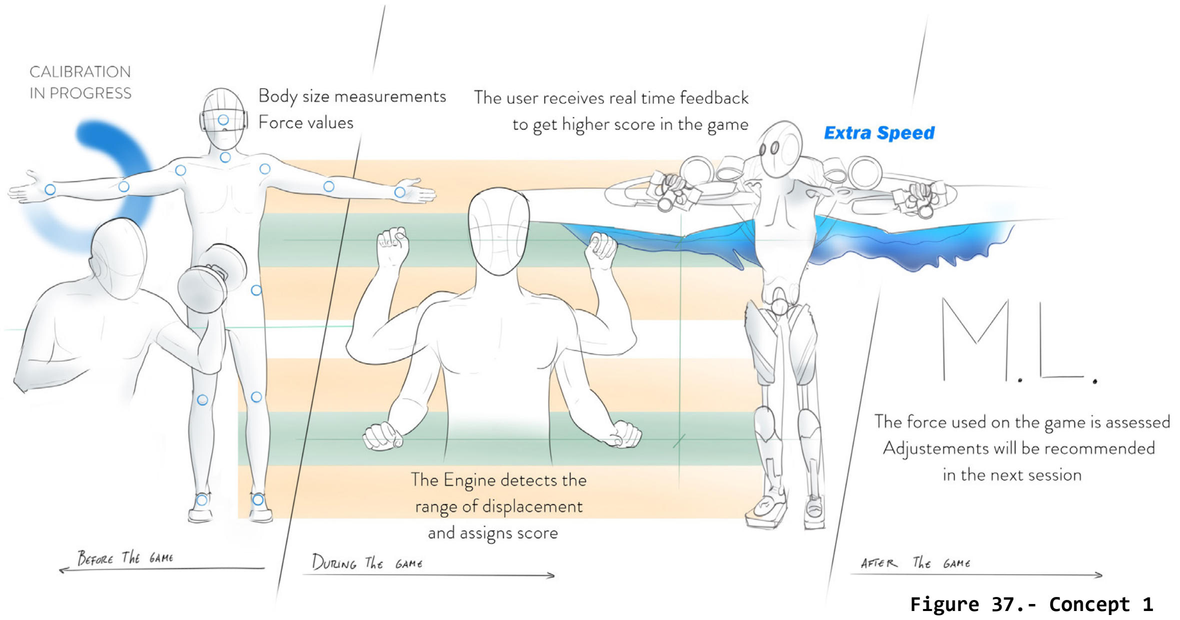


Figure 37.- Concept 1

Concept 1.- Educating a gamer. Link posture to success

This concept proposal intends to link the player's performance to the posture they adopt when exercising. Thereby, players that perform exercises in correct postures would be rewarded accordingly with valuable resources for the game itself - e.g. extra speed, points, coins, ammunition- The reward/punishment concept is normally used in games to influence or guide users towards certain decisions, and it is proven to be an engaging way to modify user's behaviour.

In this case, real-time feedback communicated through either the visual, auditive or force-feedback channels would provide users with information on how to correct their posture. How feedback affects the desirability of the proposed solution would be in fact a feature to prototype and subsequently test with users. However, the concept proposes to first through the visual interface communicate the errors and in case this does not make any effect over the user apply an adjustment in the force.

To enable a fair competitiveness among different users, the Ethereal Engine would include an initial calibration as a platform, oriented towards the adjustment of the physical interaction to the capability of each user. This tool is designed to define a specific range of motion for each individual, in such a way that people with longer upper extremity would require a broader displacement of their arms to obtain the same score than a shorter individual. In contrast, force will still be a distinctive parameter not included in the calibration to motivate users to keep improving. The reason why this distinction is made comes from the fact that games should not discriminate against people according to their permanent characteristics - such as height or other dimensions - and should motivate users to improve what it is in their power.

The calibration process not only would personalise the experience according to the user's capabilities, but also it would be used for communication purposes. The Ethereal Engine makes use of tracking technologies that are not necessarily explained to the user. This calibration process pretends to ease the real world to virtual world transition, making users part of a sci-fi/ epic experience in which they understand how the virtual avatar will perfectly suit their body.

Moreover, different training plans would be offered to users to recommend certain games and help plan workout sessions helping to fulfil their fitness goals. From a technical perspective, during the calibration process, the machine would introduce the MoCap system data, platforms' scales measurements and load cell values into a digital human body model to accurately adjust avatars to users' size. Since the user will not vary this process would run one time per session, as a first contact point with the experience.

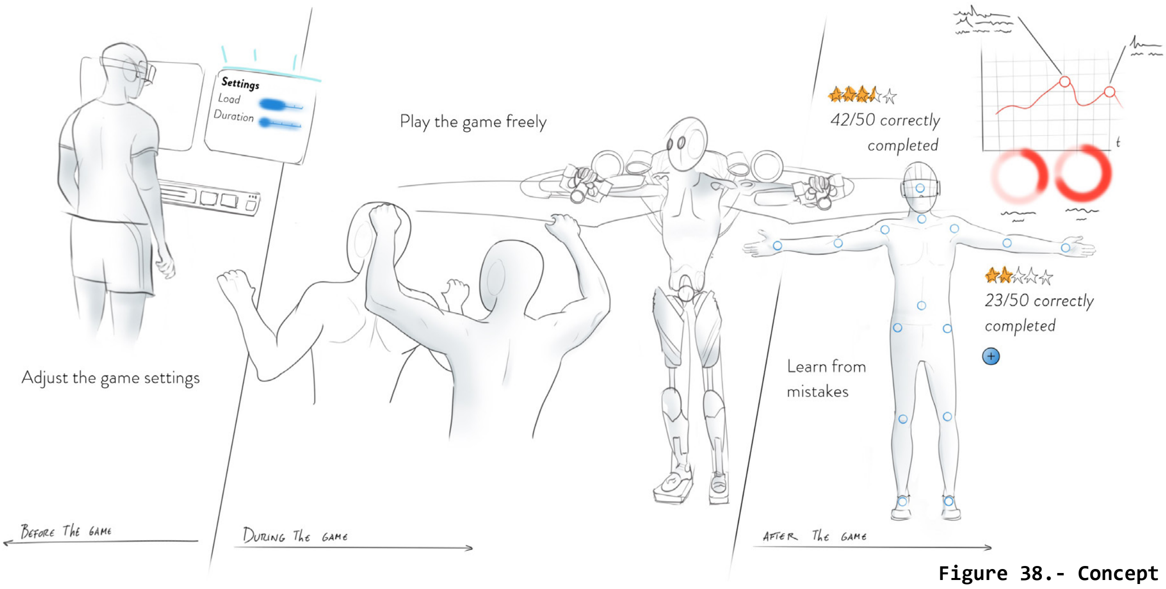


Figure 38.- Concept 2

Concept 2.- Freedom first. Usual Workout made smarter

The user adjusts the workout settings by himself. Factors such as the workout session duration, load and control motions -if applicable- are adjusted by the user. Unlike the first concept, for this second concept the workout session's smartness lies with the user. However, training plans are still offered as templates where users personalise the experience. - e.g. Cardio Paradise, Curls n' Crunches, BootyCamp, Weekend Warrior, Superman…- Right after the training, the player receives feedback and recommendations. Additionally, as in the pain scales used in physical therapy, the user evaluates some parameters to receive suggestions for subsequent workout sessions.
The reasoning behind this concept resides in the rejection that constant supervision could provoke in certain users. Thereby, the user does not feel judged during the workout session and experience is split into two distinguishable moments: workout and feedback.

The user decides whether he wants to skip the posture assessment or make the most of it. In brief, posture is understood as an independent assessment that does not condition the game, whereas the score obtained is determined by the power of exerted motions.

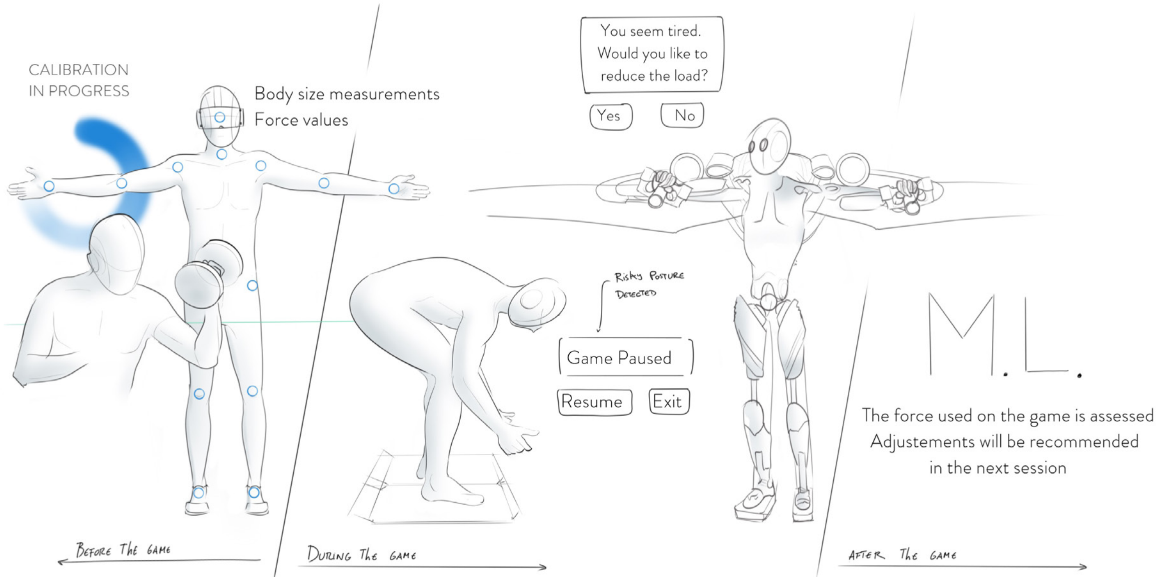


Figure 39.- Concept 3

Concept 3.- Adaptation during the game. Limit the risks

In this last concept, the Engine is understood as a companion that safeguards users' physical state. It recommends certain modifications when it notices the user being exhausted and automatically enters into a pause mode when hazardous postures are detected. The behaviour is highly influenced by physical therapist procedures.

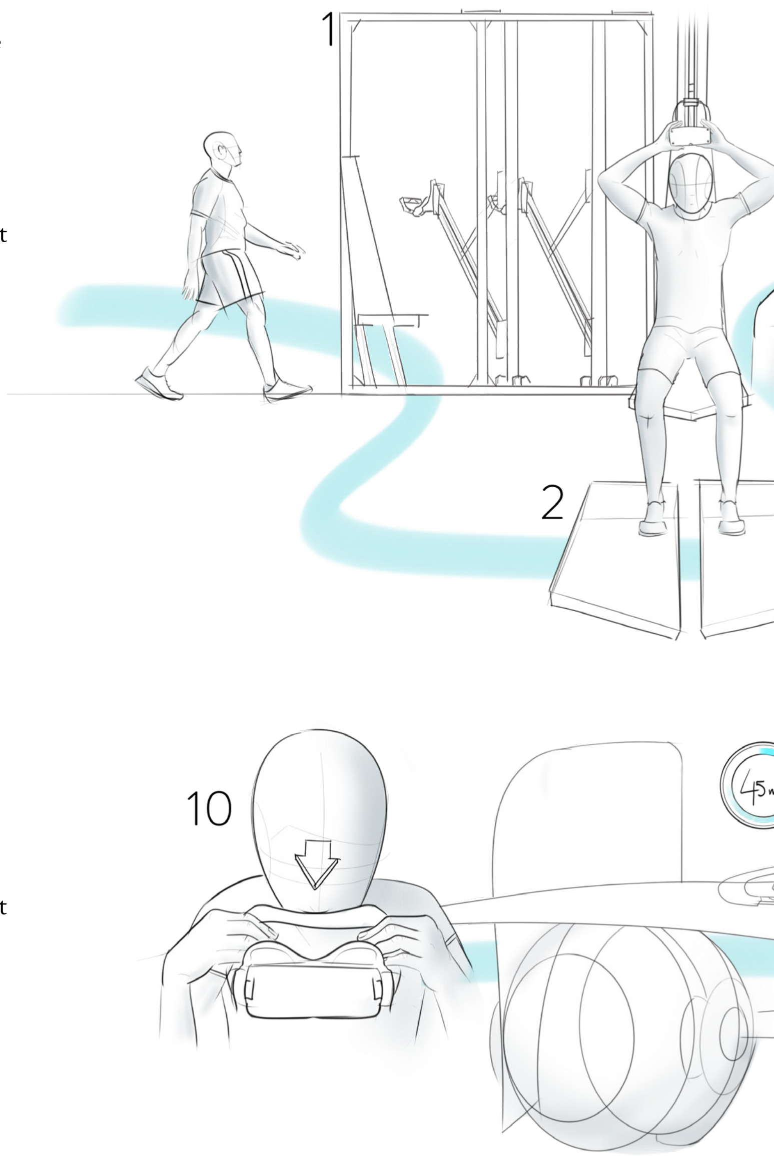
Firstly, the calibration process determines the physical limitations of the user, as a physical therapist would assess by means of a pain scale. In the second place, when risks are identified the machine restricts the bodily injury risk. However, this could limit the fun for users to take risks repeatedly.

On the one hand, the aperture of movements, their frequency evolution over time and heart rate would be used as indicators to detect fatigue. Through the visual interface, a pop-up message would recommend the user adjust the experience. On the other hand, depending on the game some postures would be triggered as dangerous for the user's physical state. When harmful posture is detected, the engine would enter a pause mode switching to free motion gradually.

In this case, the possibility of completing the experience while preserving the user's physical state is prioritised over the gaming experience. The score is not linked to the power as it was in the previous games. In fact, since the user's energy decreases incrementally as the workout progresses, a different scale such as movement fluidity together with posture could be used as a scale of success. That way, users would not plan their workout to break their own records first getting excessively tired from the following exercises. Moreover, by disassociating power to score, users would not be encouraged to push the machine to its constructive limits. The scoring method resembles the approach used in free-motion *VR* games, such as *Beat Saber*, where the score is influenced by the range of motion of certain movements and the position where you cut a block. However, different leader boards depending on the load opposition of the machine could be incorporated to preserve a distinction between players and propel competitiveness.

5.2 Envisioned Interaction

The envisioned interaction shed light on how the concepts could be integrated into the Ethereal Engine experience. *Figure 40* includes a step by step division of the user journey, laying emphasis on how virtual trainers could be incorporated in the loop.



Step 1: After booking a spot through the gym app to exercise for 45 minutes in one of the Ethereal Engine stations, the user accesses the machine.

Step 2: The user sits on the seat and right immediately picks up the *VR* headset from the frame. Alternatively, the option of linking personal *VR* headsets is considered to boost hygiene in a changing world due to the recent *COVID 19* pandemic.

Step 3: The user puts the headset on.

Step 4: By means of augmented reality, footprints over the platforms or other graphical support is shown, inviting the user to stand up and open their arms to proceed with the calibration process.

Step 5: Body shape modelling is performed. The MoCap systems provide the skeletal data and the weight scales located in the platform's user's weight. Since user's measurements do not vary along the exercise, running this calibration once can ease the system to detect certain inconsistencies derived from MoCap measurement errors.

Step 6: The user is asked to hold both grips and perform some simple movements. As the user tries to move the grip the opposition the robotic arms create gradually increases, measuring maximum executable forces in different directions.

Step 7: After the calibration process is completed, the experience starts the transitions to a virtual space, in which the user turns into a virtual avatar that perfectly suits their body.

Step 8: The user accesses from the main menu the different games/workouts. From this main menu different training plans -recommending certain games/workouts- and a personal profile can be accessed as well.

Step 9: Different games are played until the Ethereal Engine booking time is over. The virtual trainer would mainly affect this step. The strictness, explicitness, and immediacy of the feedback are the qualities to further explore.

Step 10: The user finishes the workout session, going through an outro transition to the real world.

As additional notes to further consider, step 6 or somewhere between step 8 and 9 warm-up exercises could be included to reduce the bodily injury risk. It could either be introduced as part of calibration or as a part of a tutorial in which the user gets ready for certain movements necessary for that game/workout.

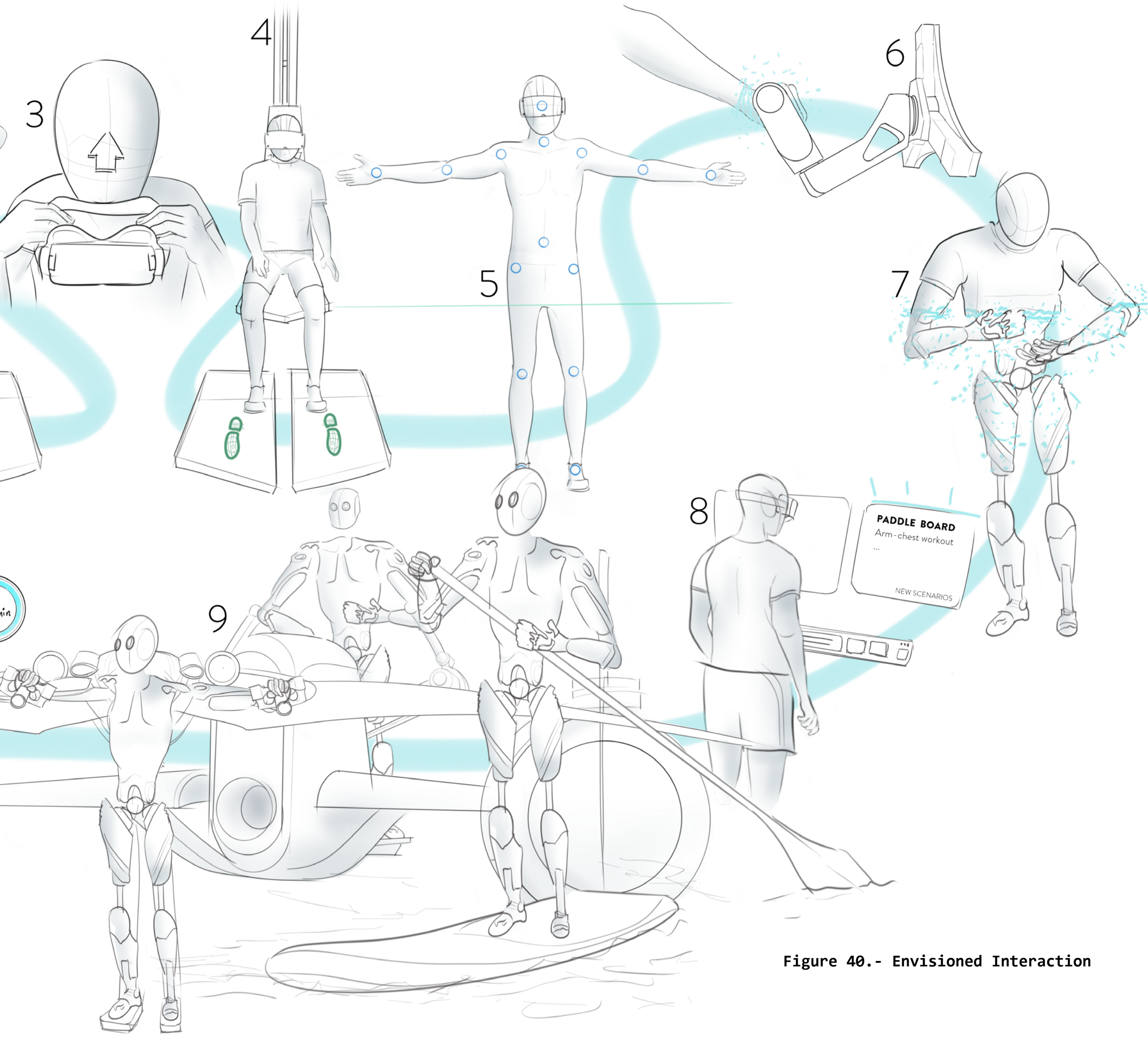


Figure 40.- Envisioned Interaction

5.3 Concept discussion

This section aims to dive deeper into the intrinsic qualities of the presented concepts. Each concept proposes an alternative to implement a virtual trainer in the Ethereal Engine. However, each of them prioritises certain values. These qualities are the strictness, explicitness, and immediacy of the feedback.

With regard to how these are represented in each concept, *Educating the gamer* looks into the option of unconsciously and immediately affecting the user behaviour. Conversely, *Freedom first* understands the virtual trainer as an additional optional feature, not strict at all. Lastly, *Adaptation during the game* proposes a strict, explicit and immediate influence limiting the workout when incorrect posture is detected. *Figure 41* shows an initial hypothesis of how these qualities apply to each concept.
In this context, one could wonder: How is this valuable for the Ethereal Engine? Motivating correct workouts at an engaging level could be a key feature for the Ethereal Engine to shape and lead the *exergaming* industry. Similarly, another relevant question is: How could we make the users rather use the virtual trainer than not use it? Indeed, some concepts propose to leave up to each user the decision of benefiting from the virtual trainer, however including postural support at an engaging level could derive in a win-win situation, in which realism, and safety will come hand in hand.

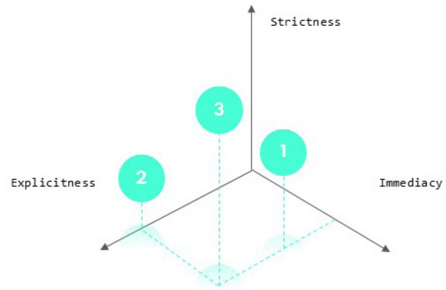
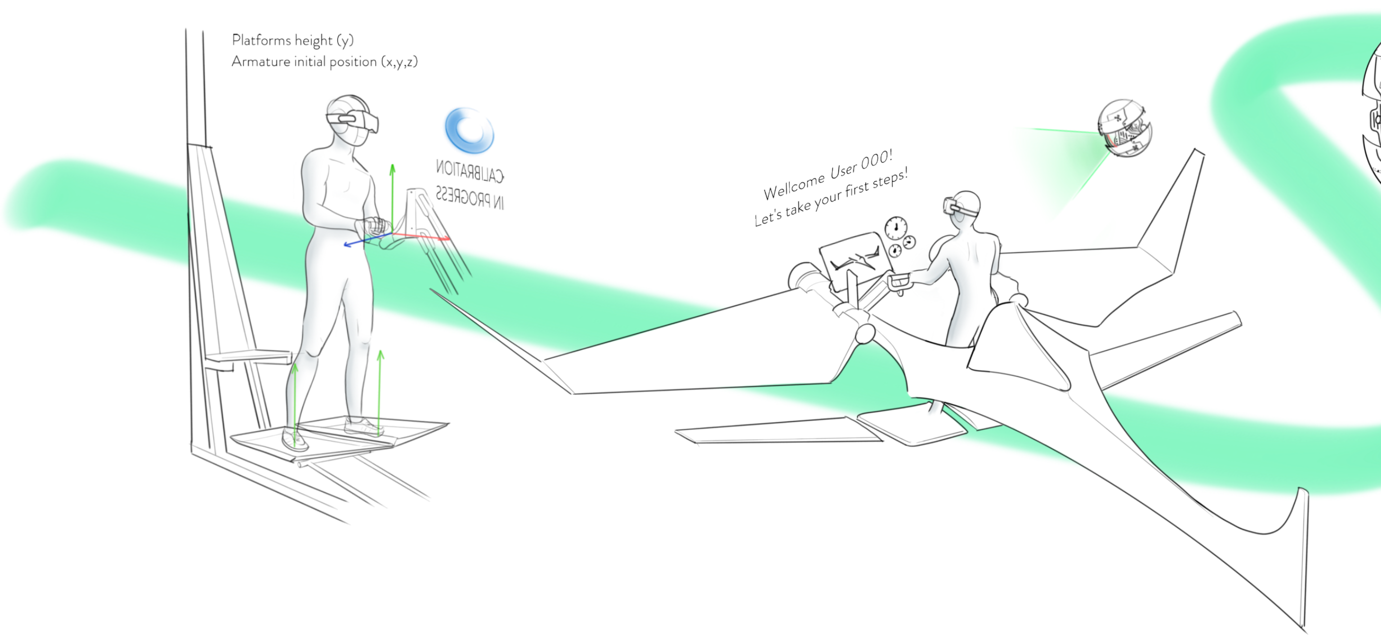


Figure 41.- Concepts assessment considering the explicitness, strictness and immediacy

Next, the three variable qualities are discussed.

- **Strictness of the feedback.** Imposing certain behaviour can limit the fun, provoking rejection in certain users. Too strict feedback can lead the user to constantly criticise his own performance, and even doubt his own capabilities. However, an optional virtual trainer feature leaves the user at their own risk, missing an opportunity to make use of the smartness available. In this scenario, the opportunity of inspiring instead of imposing rewarding correct postural behaviour is spotted to



be further tested.

- **Explicitness of the feedback.** Exploring opportunities that would not break the immersion, might be useful to unconsciously modify the user behaviour. The aforementioned concepts work at different consciousness levels, changing the way information is conveyed.

- **Immediacy of the feedback.** The last criterion comprehends the moment in which the feedback is conveyed. The feedback could be offered during the workout, right after the workout or as a suggestion in future training sessions. These alternatives differ from each other in the idea of splitting or keeping together the training and feedback moments. Additionally, the option of offering feedback at different levels -conscious or unconscious- at different stages of the experience is also considered.

In the following chapters, the prototyping performed to evaluate the following features is included, obtaining certain clarity in the desirability of the proposed solutions. The prototype setup not only fulfils this testing purpose but also further develops the experience of the Delft Engine, by putting work together the MoCap system and *Oculus Quest* in a *VR* environment.

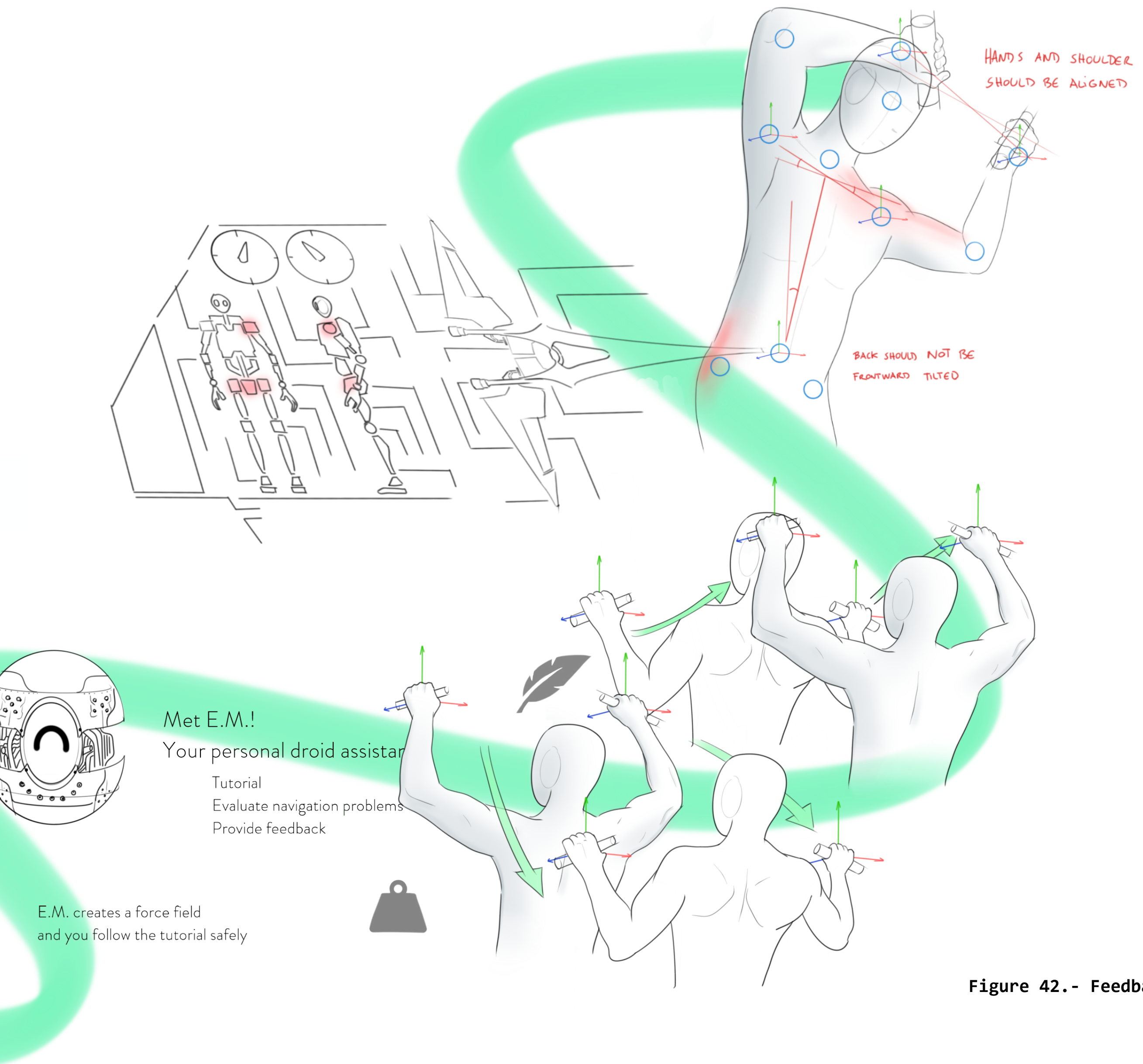


Figure 42.- Feedback idea

Figure 43.- Working on the robotic arms' prototype

- C H A P T E R 6 -

Prototyping

This chapter documents the development of Delft's prototype in order to set an experiment that would clarify the desired qualities for implementing a virtual trainer. Critical design decisions derived from early prototyping will be presented, such as selecting *MoCapForAll* and its implementation in *Unity*.

In addition, the resulting progress from the elbow to elbow collaboration with Moritz von Seyfried on the *Delft Engine* prototype is presented.

6.1 Introduction

Developing a prototype that shows off certain features of the proposed conceptual solutions is understood as the first milestone on the Delft prototype development journey. In fact, by the time this graduation project starts, no prior effort on the *VR* implementation has been done in Delft. Thereby, this chapter apart from documenting the development process tries to illustrate and clarify for future students how to deal with *VR* games development in *Unity* in an efficient way.

The main objectives for prototyping are listed down below:

- Create a system that captures user movement fulfilling the list of requirements, laying special emphasis on cost and occlusion reduction.
- Create a minimum viable system that exhibits the potential of virtual trainers.
- Create an experimental setup that could help Ethereal Matter smartly integrate a virtual trainer into the engine.

As an intent to specify a measurable scale to assess the development level of the prototype, it is expected to reach a Technology Readiness Level 4 - or *TRL4*, which means that the system would be proven to work in a lab. It is not considered a *TRL5* which comprehends the implementation of the technology in a relevant scenario, due to the fact that there are certain conditions such as the lighting, camera positioning, and robotic armatures positioning that are not incorporated yet.

Said so, the process starts with the prototyping of MoCap systems resulting in a final decision for the implementation. Next, the game engine *Unity* is studied, with the ultimate goal of setting up a *VR* experiment that could provide answers to questions related to the virtual trainer. Lastly, the *VR* experiment is developed first as a demo to be controlled by means of a mouse and keyboard, and subsequently adjusted to *VR*.

The experiment seeks to obtain some clarity on the desirability of previous concepts, playing around with the three qualities presented in *Chapter 5.3 Concept Discussion* -there are strictness, explicitness and immediacy-. By means of *Unity* software a simple *VR* experience in which users do squats while lifting an object with a certain weight is designed. And different feedback types that simulate virtual trainer features are included. Considering the fact that a machine that opposes the movement is not available in Delft, a real object is recreated in *VR* and linked to the *VR* controllers to match motion in both worlds. A 3D printed support is designed to firmly attach the controller to the object.

As an additional section to bring the prototyping performed along this Graduation project to an end, the steps towards the assembly of the first physical prototype in Delft are included.

6.2 MoCap system

6.2.1 MoCap system selection

This section presents the reasons that lead to the decision of integrating multi camera based MoCap technology for the Delft Engine are presented. *Figure 44* presents the followed method towards the selection of a MoCap solution.

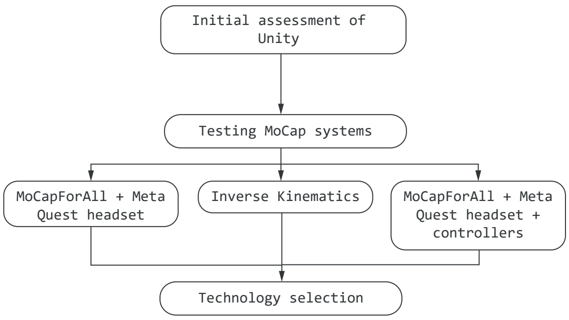


Figure 44.- MoCap system selection procedure

The literature review clarifies that currently, depth cameras are the most accurate way to avoid any kind of collision-related risks. However, due to the fast evolution of triangulated multi *RGB* camera systems together with the development of posture detection, *ML* based solutions emerge as a low-cost alternative solution that would considerably reduce occlusion.

Apart from the literature study, two different prototypes are built to experience different alternatives. These technologies are: Inverse Kinematic and *MoCapForAll*. These prototypes are considered Functional Prototypes according to Loughborough University and capture the key function of the MoCap system (Evans, 2011).

The Inverse Kinematics approach provides an accurate solution for hands and head tracking, but for the lower limbs tracking including trackers on the feet would be necessary. Furthermore, the elbows are positioned considering the most likely position which is not reliable for the safety boundary definition.

The *MoCapForAll* system instead, presents certain deviations when posture gets hard to detect due to occlusion. This system is first tested by intersecting the camera recording with the skeleton data, instead of loading it in *VR* since this entails solving certain challenges mentioned in *Chapter 6.2.3 MoCapForAll implementation in Unity.*

Table 2 shows a comparison of the different commercially available MoCap systems. Note that *ML* based systems are just software packages, whereas *RGB-D* sensors include the hardware required for detection. All systems included requires an additional processing unit. But in terms of computational cost, all cases except the Inverse Kinematics one, present a considerable consumption, which normally is tackled using development kits such as *Jetson Nano*, where the information is processed.

Name	Tecnology	Price €	Resolution	Fps	FOV
Kinect Azure	RGB-D	379.50	W4416x1242 N 640x576 RGB 3840x2160	30 30 30	120° x 120° 75° x 65° 90° x 59°
ZED 2	RGB-D	449	4416x1242 3840x1080 2560x720 1344x376	15 30 60 100	110° x 70°
Captury	ML multi-camera	2000 lic/year	x	x	x
MoCap-ForAll	ML multi-camera	73 license	x	x	x
Inverse Kinematics	Inverse Kinematics	0	-	-	-

Table 2.- MoCap systems comparison

For providing the reader with a holistic perspective:

- *Microsoft LifeCam Studio* with 1920 x 1080 resolution, 3Mpx, 30fps and a diagonal field of view of 75° can be purchased for 37.50€ in an online vendor.[]

- *2K QHD Depstech Webcam* with 2560 x 1440 resolution, 3Mpx, 30fps , and a diagonal field of view of 90º can be purchased for 38.99€ in an online vendor.[]

Purchasing two cameras for each of the multi-camera solutions and adding the price of the software the prices of alternatives are initially compared. Said so, a multi-camera system using *MoCapForAll* for instance, would cost around 150€ -excluding the processing unit-.The fact that both systems, either depth *RGB* or multi *RGB* camera fulfil the technical requirements for successfully implementing the proposed concepts brings the chance to further experiment in parallel -US and the Netherlands-both solutions.

Said that, the application of multi camera based MoCap system is targeted as the most desirable path to continue with in Delft, exploring a different opportunity that could result in a valuable contribution to this intercontinental collaboration project.

Finally, considering the requirement of real-time tracking, and the limited software available at good a quality/price ratio - understanding as synonyms of quality a low latency and good accuracy- *MoCapForAll* is acquired for further develop the Delft Engine.

6.2.2 *MoCapForAll*

MoCapForAll is a multi-camera motion capture software developed by Akiya-Souken Research Lab -Osaka, Japan-. This software is the result of an ongoing research project and is frequently updated using the feedback obtained from a Discord channel where a wide network of users and developers connect.

It provides users with a posture detection system that replicates the skeleton using a point cloud of 16 nodes It offers as well a face expression replication system, but currently it does not seem a valuable feature considering the head detection limitations when using a *VR* headset. *Figure 45* shows an example of *MoCapForAll* used for animating an avatar.

It requires an initial calibration process consisting in an intrinsic and extrinsic phase.

The intrinsic phase comprehends the adjustment of the software to camera settings, such as the focal length and frame per seconds. This is done using a calibration pattern that needs to be printed, preferably in an A4 sheet. From the Akiya-Souken Research Lab, they recommend disabling the autofocus on webcams not to cause problems.

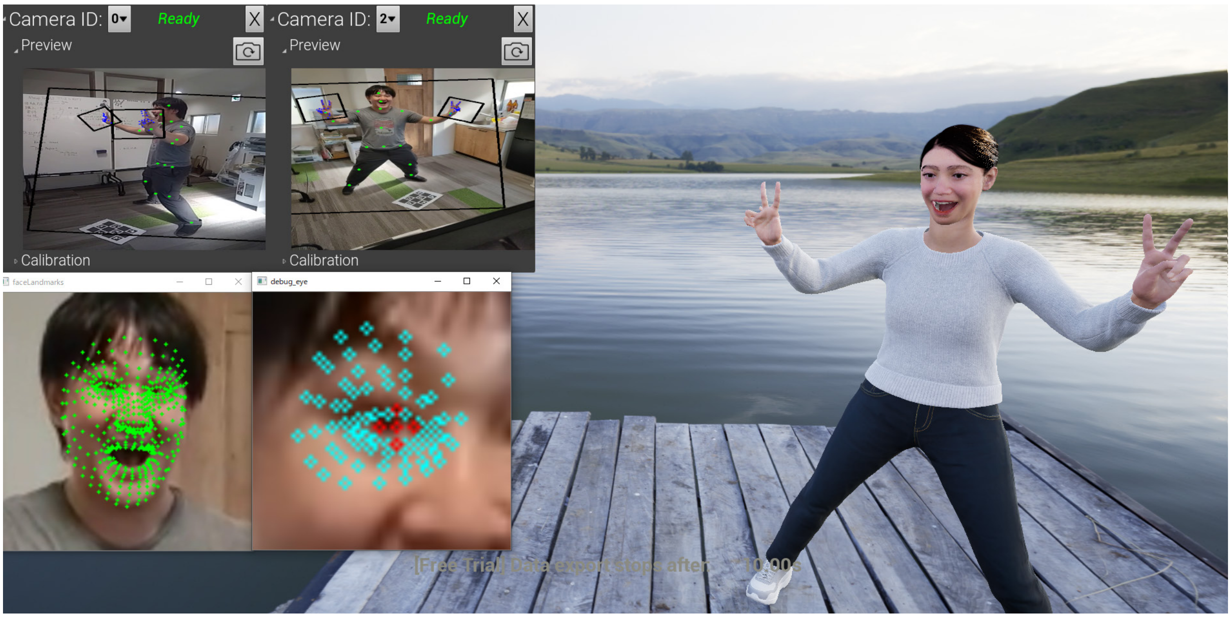


Figure 45.- *MoCapForAll* user interface (Akiya Research Institute, 2021)

In the extrinsic phase the relative positioning between cameras is calculated. For this purpose, *MoCapForAll* supports four different alternatives: *ChArUco* board, *ArUco* cluster, Diamond cluster, and human motion. Except for the human motion, which does not require any additional equipment, the rest of the techniques use certain canvases for pattern recognition, as shown in *Figures 46 & 47*. From the different alternatives *ChArUco* board is selected as it results in the best accuracy. In this case, printing it in an A2 sheet results the best.

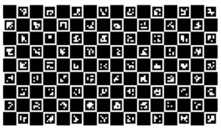


Figure 46.- Intrinsic board (Asaba, 2022)

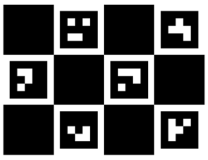


Figure 47.- Extrinsic ChArUco board (Asaba, 2022)

It worth to mention that this software just works with stationary cameras. Similarly, it offers the possibility of saving camera relative position for permanent installations. This last feature makes it perfect for the Ethereal Engine, since there will be no need of calibrating the cameras before every workout session.

6.2.3 *MoCapForAll* implementation in *Unity*

MoCapForAll offers a plug-in to transfer the nodes to *Unity* in real time. As previously mentioned in *Chapter 2.1.2 System architecture, understanding machine's operation*, *Unity* is the cross-platform software where the secret sauce of the Ethereal Engine happens. It is a flexible software that allows users to write their own pieces of code and create plug-ins for an innumerable variety of purposes.

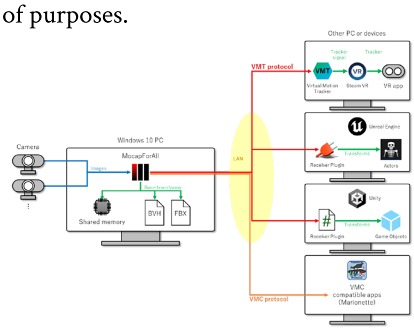


Figure 48.- *MoCapForAll* compatibility (Asaba, 2022)

Implementing *MoCapForAll* in *Unity* is as easy as running both software pieces at the same time, having included a script in a *GameObject* in *Unity* that enables the data transfer. However, rigging an avatar supposes an initial challenge. Each of the nodes represents a certain part of the body as illustrated in *Figure 49*. But, depending on the definition of the avatar, the rotation of the nodes needs to be adjusted to correctly represent the human body.

Although the piece of code required for this action is simple it requires manual iteration to create the perfect rig. *Figures 50 & 51* illustrate the transition from a correct positioning of the nodes to correct orientation.

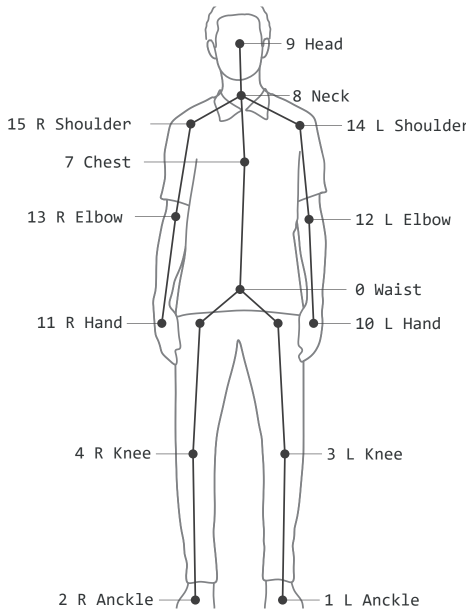


Figure 49.- *MoCapForAll* nodes identification numbers

Figure 50.- Nodes position corrected

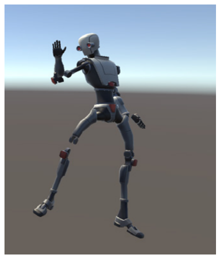


Figure 51.- Nodes orientation corrected

Similarly, combining *MoCapForAll* with a *VR* equipment, in this case Meta Quest 1, generates misalignments between both systems that need to be corrected. *Figure 52* tries to illustrate the encountered problem.

Down below the step-by-step procedure to fix this issue is included:

- Create a parent object that contains the imported *MoCapForAll* nodes. Name it *MoCapPoints*.
- Create a parent object that contains the *VR* equipment -headset, plus controllers if it proceeds-. Name it *VR Rig*.
- Move the centre of *VR Rig* to a point in the space where both heads will be aligned. This step will resolve the position misalignment. However, the body orientation will not correspond to the body's. -See *Figure 53*-.
- Evaluate which of the *VR* headset's axis correspond to the head's axis.
- Once you know how axis are related, calculate the relative rotation of each axis.
- Add the rotation to *MoCapPoints*.

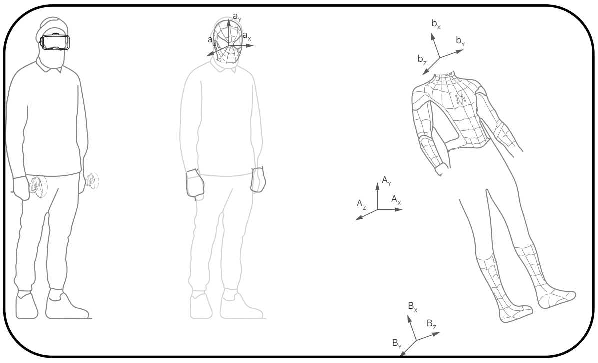


Figure 52.- Initial misalignment

6.2.4 MoCapForAll first conclusions

From the implementation of MoCapForAll in a VR environment the following conclusions are made:

The alignment problem is solved, however depending on the technology implemented -e.g. *Oculus, HTC, MoCapForAll, Kinect, etc.*- the reference axis will change and certain iterations will be required to understand what axis are related among themselves.

Additionally, by comparing the system with inverse kinematic approach these are the conclusions that can be drawn:

- Multi-camera-based MoCap is much more enjoyable, enabling the VR replication of legs and elbows more accurately.
- Multi-camera-based systems can be used to adjust the avatar 3D model to user's by means of Digital Human Modelling approaches.
- Both systems offer a fluent motion.
- Inverse kinematic reduces the power consumption.
- In the current multi-camera-based MoCap setup, cameras do not cover full range of motion.
- In the current multi-camera-based MoCap setup, alignment is not completely solved due to time constraints, but it has been proved that it can be solved.

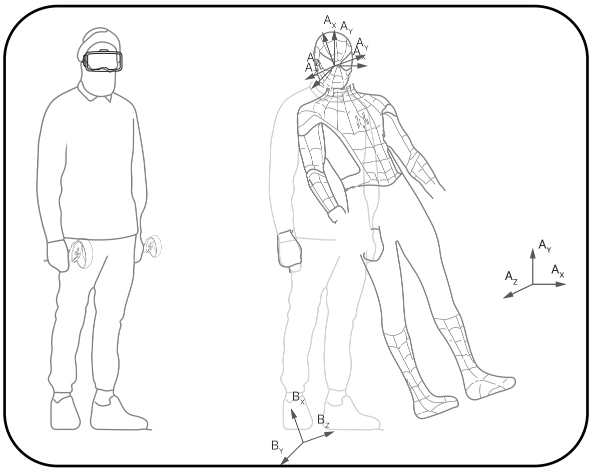


Figure 53.- Position correction

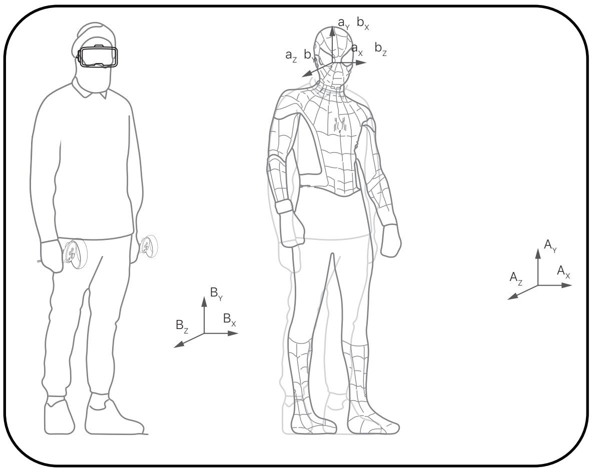


Figure 54.- Rotation correction

6.3 Setting up the experiment

Once the data retrieved from *MoCapForAll* is integrated in the environment of *Unity*, a process towards the establishment of the experiment takes place. *Figure 55* illustrates the procedure followed for the experiment definition.

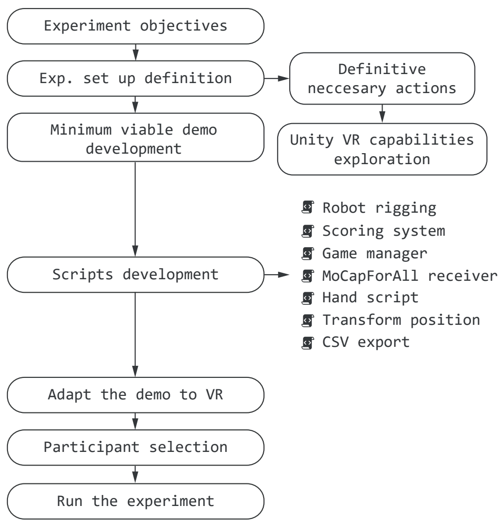


Figure 55.- Experiment development process

6.3.1 Experiment objectives

- Create a minimum viable system that exhibit the potential of virtual trainers.
- Obtain results that will clarify the desired features of a virtual trainer to subsequently implement it in the Ethereal Engine.

6.3.2 Experiment setup definition

The experiment consists of a game that provides participants with different feedback on their performance doing squats while lifting a water jug. Being noted as variables of interest in the explicitness, immediacy, and strictness of the feedback, three different experiments are configured where these three knobs are present at different levels.

In each of the experiments, participants are asked to do 10 squats while lifting a water jug. Depending on how the water jug is aligned with a theoretical line the user receives a score from 0 to 100 every time they complete an upward or downward motion. For each of the motions -up and down- there is a line. That theoretical lines derive from a calibration process in which the user's height is used to position those in the space.

Additionally, there is a threshold that needs to be exceeded for the *VR* system to understand the user completes a full motion. For instance, if the user slightly moves the water jug up or down the system would not count this as a squat.

Continuing on the feedback alternatives, a description of each of these is included below:

- Experiment 1 makes use of a virtual canvas consisting of three stripes that visualize the correct displacement of the water jug.
- Experiment 2 provides participants with statistics on their performance when they reach half of the
- Experiment 3 visualizes a pop-up message, letting the user know if they displace excessively high or low water jug.

Considering all the mentioned actions, the next step consisted in translating this desire into a working prototype in *Unity*. Regarding the experiment, *Chapter 7.1 Experiment* further elaborates on its details -e.g. protocol participants and results-.

6.3.3 Unity basics

Unity is software where developers can create their own games, either 2D or 3D, for multiple platforms, from smartphones to *VR*. *Figure 56* shows a screenshot

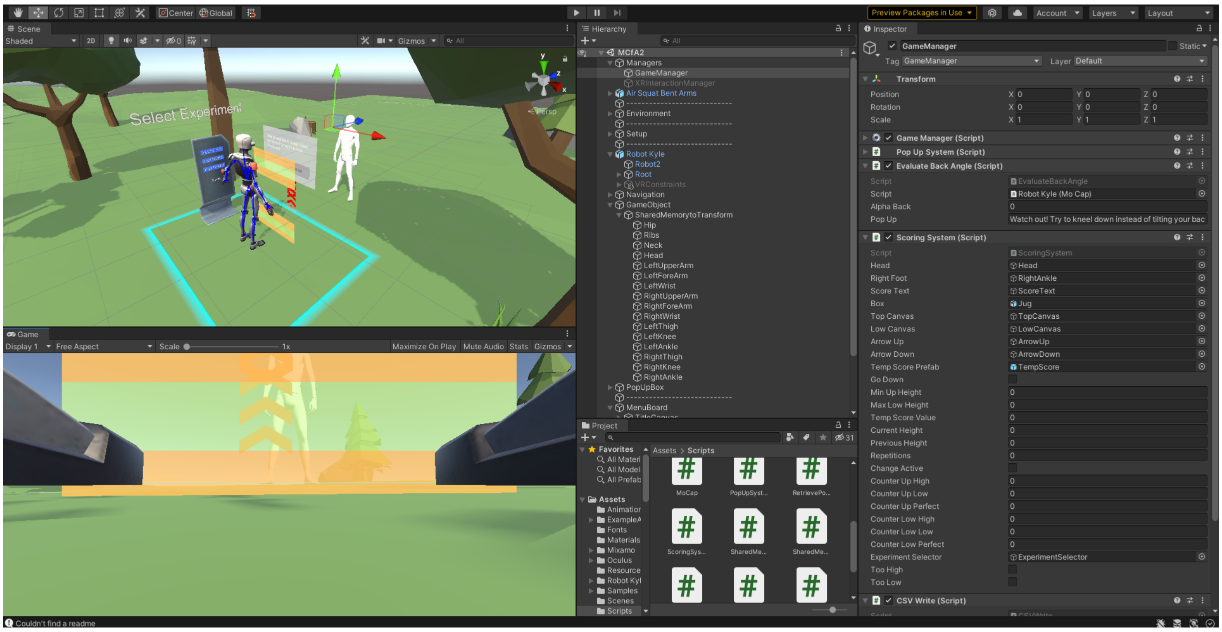


Figure 56.- *Unity* visual interface

of the visual interface of this software.

The hierarchy panel includes all the *GameObjects* present in the scene. *GameObjects* are elements -either empty or a geometry asset- which per se do not present any functionality. *Unity* makes use of parent and children-based structure, which enables certain interdependencies and possibilities when it comes to writing your own scripts.

In the inspector panel, the scripts linked to the selected *GameObject* are shown. The scripts enable *GameObjects* to perform certain actions as desired. In terms of scripts two main alternatives are frequently used: monobehaviours that every timestep are run, or coroutines that enable certain delays between repetitions.

Besides that, it is worth mentioning that *Unity* incorporates a package manager where additional software plug-ins can be installed, such as *OpenXR*, a fundamental package to develop applications for Steam *VR*. This package includes sample scenes to enter *VR* worlds and play around for the first time.
In the following chapters these terms will be used to explain the construction of the architecture of the prototype.

6.3.4 Minimum viable Demo

In this section the development of the *Unity* file to successfully create the aforementioned experiment is developed. First an initial demo controlled by mouse and keyboard is developed, and adjusted to *VR* a posteriori. Next, some of the most important scripts to set up the experiment are included.

- *SharedMemoryToTransform*: This monobehaviour script receives the .transform of the skeleton nodes from *MoCapForAll* and overwrites it in the desired *GameObjects*.

- *RobotRig*: This monobehaviour script links the *GameObjects* previously transformed to a virtual avatar and allows the user to manually introduce an offsets to correct the position and rotation.

- *GameManager*: This coroutine manages the change of state along the game. Five different states are defined: *Start, PlayMode, Pause, Stats and Victory*. Each of these has a certain trigger that controls the change from state to state.

- *TransformPosition*: This monobehaviour script corrects the alignment problem, moving the *VR* headset's system of reference to a new spot to be perfectly aligned with the head measured with *MoCapForAll*. The functionality of this script is activated with the third click of the mouse.

- *ScoringSystem*: This monobehaviour script has three different functions. In the first place, it calibrates the system to the user's height when the calibration function is called. In the second place, it manages the motion by means of a boolean that triggers the need of going downward or upward. Lastly, in the third place, it calculates a certain score depending on the distance from the perfect theoretical line.

- *EvaluateBackAngle*: This monobehaviour script calculates the back angle, considering the angle form between the vector produced by hips and neck with the horizontal plane.

- *HandScript*: This monobehaviour script allows the hand to interact with *UI* elements, such as pop-up boxes and other buttons.

- *PopUpSystem*: This monobehaviour script manages the pop-up messages.

- *CSVExport*: This script exports the back angle position and box height to a *CSV* file.

In *Appendix 4* the scripts created to perform the aforementioned actions are included. Lastly, from the digital repository the *Unity* file can be retrieved for further development. Note that *MoCapForAll* and *Steam VR* need to be installed and running on your PC to run the program. Similarly, in case of creating new files for *VR* development make sure that you install the necessary packages from the *Package Manager* and *Unity Assets Store*.

6.4 Resulting system architecture

As last incorporation to the chapter, the resulting system architecture is presented in *Figure 57*.

In contrast to the original system presented in *Chapter 2.1.2 System architecture*, it can be observed how the prototype is not fully completed, missing the mechanical components.

Furthermore, *Kinect Azure* is replaced by *MoCapForAll* and just one of the controllers is used in this case due to the experiment configuration.

Despite not being included in

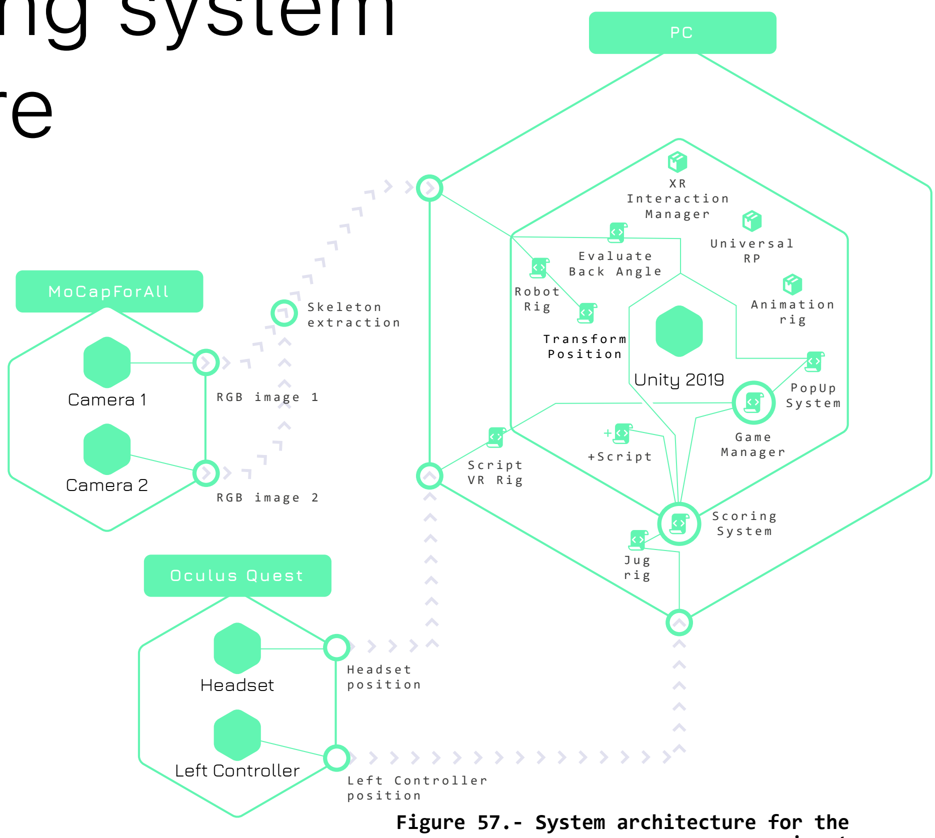


Figure 57.- System architecture for the experiment

Figure 57, the physical prototype is further developed -reported in *Section 6.4.1 Changes implemented in the Delft prototype-*.

6.4.1 Changes implemented in the Delft Engine

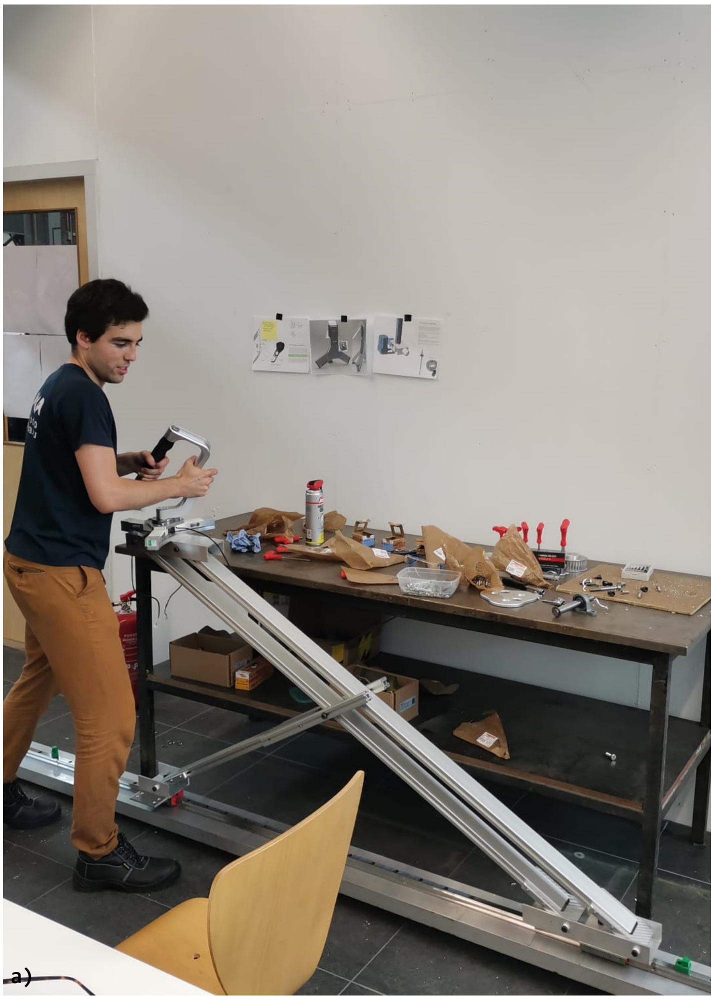
In parallel to this graduation project, in order to satisfy one of the main goals of the Ethereal Matter project in Delft - creating a working prototype that could enable an intercontinental VR physical experience- certain activities are conducted to manufacture and assembly a physical prototype. These actions are listed below:

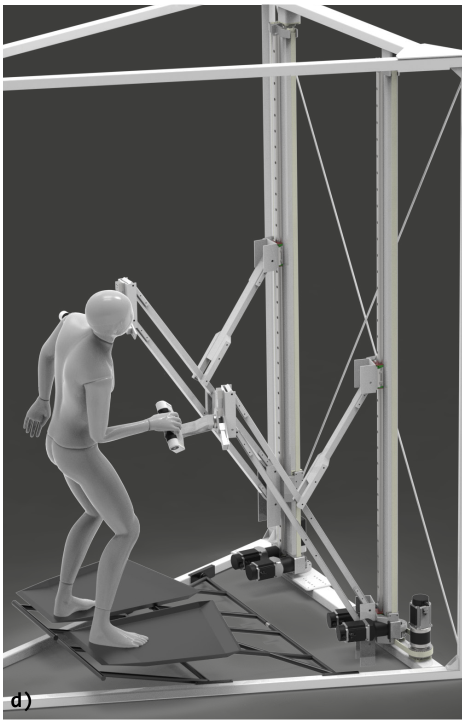
- Adaptation of the CAD design from the imperial system to metric.
- Adaptation of the components to be *CNC* milled considering the minimum relocations with a 2,5 axis machine, seeking a decrease in the manufacturing cost.
- Design of new connectors that would ease the assembly.
- Detailed drawings to explain the requirements of each piece to the *CNC* milling machine's operators.
- Find European suppliers for the necessary components to assemble one robotic arm. These are pulleys, belts, belt clamps, linear rails, carriages, aluminium tubes and aluminium blocks.
- Arrange purchases and keep track of their status by contacting the university.
- Basic machinery operations (drilling, sawing and tapping) to assemble the robotic arms.
- Plastic bearings design and 3D printing for saving time and money.

By the end of the Graduation project, all the mechanical components for assembling one robotic arm are at our disposal in the Dream Hall workshop. In fact, almost all the mechanical components are assembled end effector's full 3D motion, as it can be seen in *Figure 58a*. TThis is understood as a positive result to communicate to future teams what the system looks like, and how components interact with each other. Moreover, the fact that suppliers have been already contacted and included in the university payment system will save precious time for these future teams.

Figure 58 shows some of the activities conducted along the project. In addition, the knowledge derived from these actions is included in *Section 9.2 Recommendations for future team.* Thanks to the in-house manufacturing process, we understood the importance of double-checking every step and another aspect of how to approach the manufacturing for future teams not to ruin any component.

Lastly, other actions performed in order to obtain exposure to the Ethereal Engine are performed, such as poster design, rendering and videos.





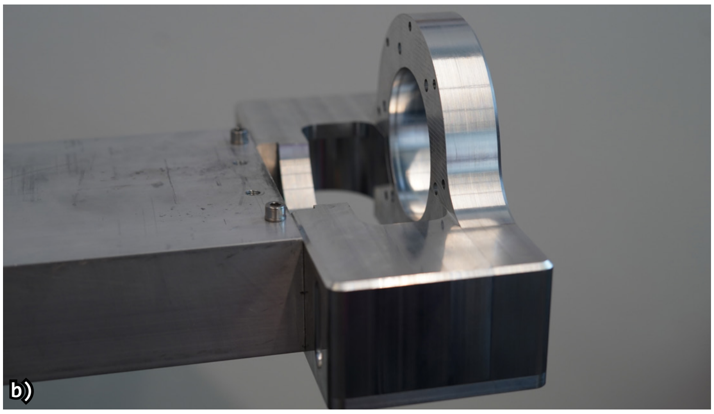


Figure 58.- *Delft Engine manufacturing shoots. a)Experiencing for the first time the motion of the full armature assembly; b)CNC milled components; c) Moritz tapping holes ; d)Delft Engine concept design ; e)CNC milling of the motor mount components using the Dream Hall's facilities*

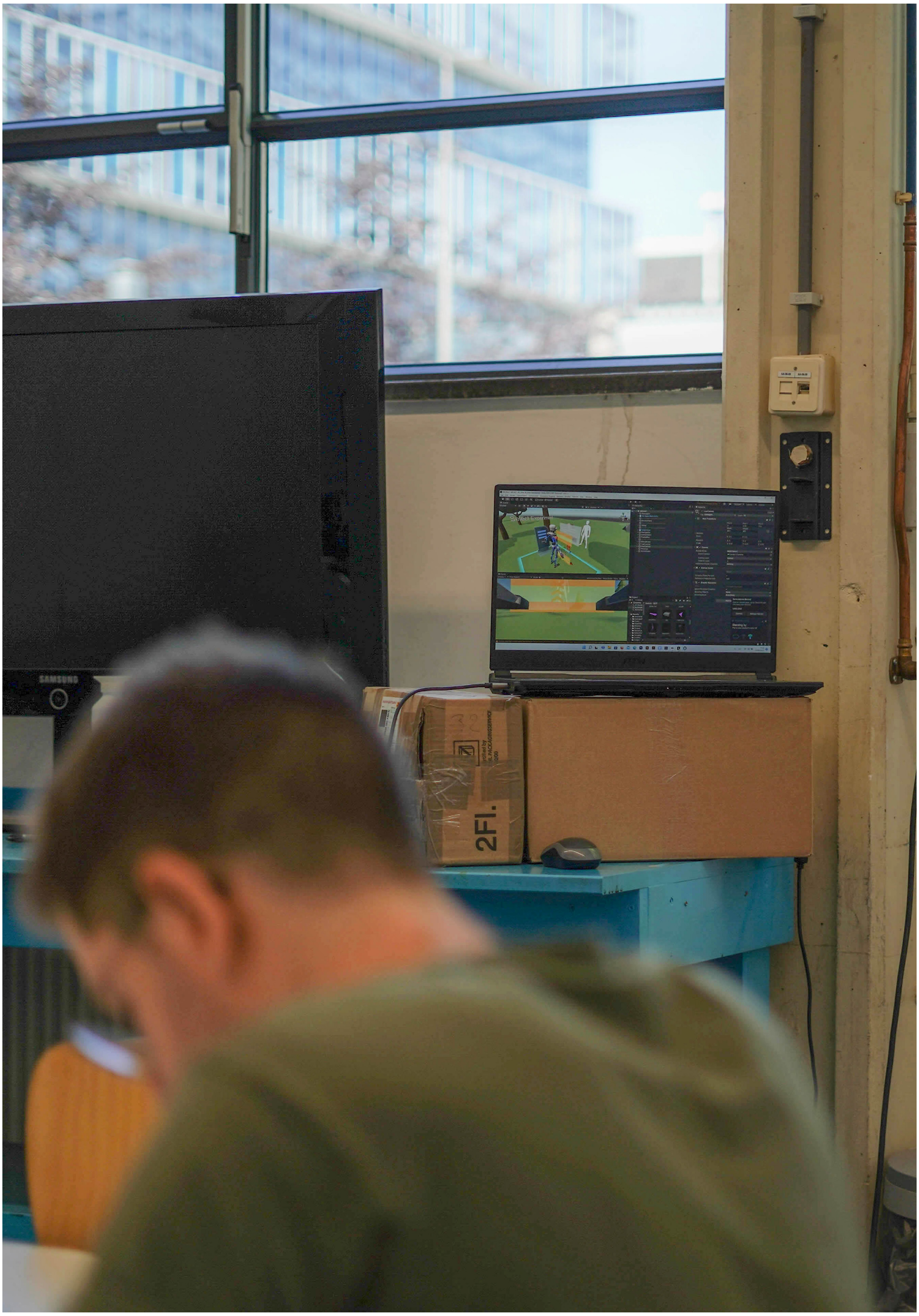


Figure 59.-One of the participants filling up the questionnaire in the foreground. Laptop running the *Unity* file in the background

- C H A P T E R 7 -

Evaluation

This chapter elaborates on the experiment performed to assess the concepts. Once a VR setup that integrates MoCap system and Oculus headset is developed, 16 participants are invited to participate in the experiment that seeks an answer on the desired tuning of the feedback in terms of explicitness , immediacy, and strictness.

By including a questionnaire and recoding participants' positional data throughout the experiment, perception and performance-related results are contrasted, shedding light on the suitability of the three feedback alternatives -visual life feedback, statistics and pop-up messages-.

7.1 Experiment

This chapter further elaborates on the information presented in *Chapter 6.3 Setting up the experiment*, presenting the experiment protocol, participants, and results.

7.1.1 Research questions

The main research question that wants to be answered through this experiment comes from the design vision:

- **What is the desired tuning of a virtual trainer in terms of explicitness, immediacy and strictness of the feedback?**

As anticipated in *Section 5.3 Concept discussion*, there is no clear evidence on how these *knobs* should be adjusted to obtain a safer experience while keeping it challenging and fun. In fact, depending on the risk level it might be a feedback solution that could work better. Therefore, by knowing the perception of each of the alternatives by potential users, reasoned decisions on how to design an engaging interaction that leads the users to self-correct their posture could be made.

Additionally, another sub-question that originally was not foreseen popped up during the experiment:

- How including a load in VR - in this case static- can have an effect on the interaction?

Considering the fact that the Ethereal Engine has no predecessor in the field of virtual trainers fused with force feedback systems, how the constant need of holding a handle -or other- could affect the interaction is discussed.

7.1.2 Experiment protocol

In *Figure 60* a schematic representation of the experiment protocol is included.

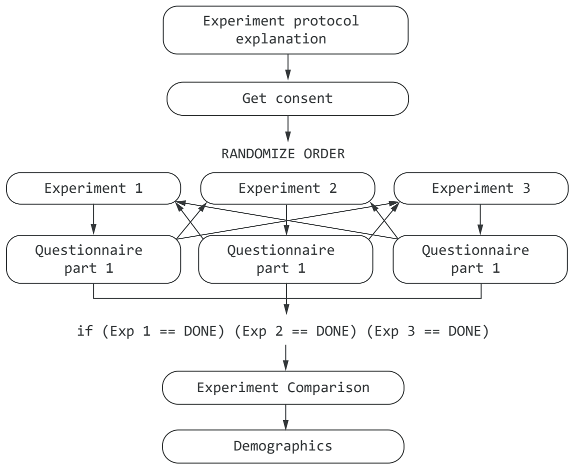


Figure 60.- Experiment protocol

As a preparation activity, I annotated the experiments' order for each participant. The experiment session starts with an explanation of the objectives, procedure, and data treatment. Next, participants are asked to give consent by clicking a next page button in a questionnaire -the full questionnaire is included in *Appendix 5*-.

Afterwards, the participant put the headset on in the experiment area and is asked to extend laterally their arms to calibrate the system-see *Figures 62 & 63*-. In a randomly selected order, the participant conduct one experiment by doing 10 squats and fills the corresponding part of the questionnaire 3 times -see *Figures 64, 65 & 66*-. Lastly, the participant fills few more questions that compare experiments and others

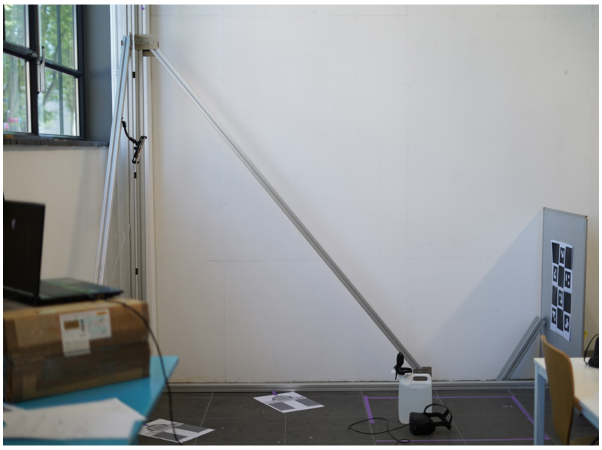


Figure 61.- Setup. Smartphone and computer webcam pointing at the experiment area -in purple- where the headset and water jug are found

Figure 62.- Participant adjusting the Oculus headset

Figure 63.- Participant opening his arms while calibration is happening

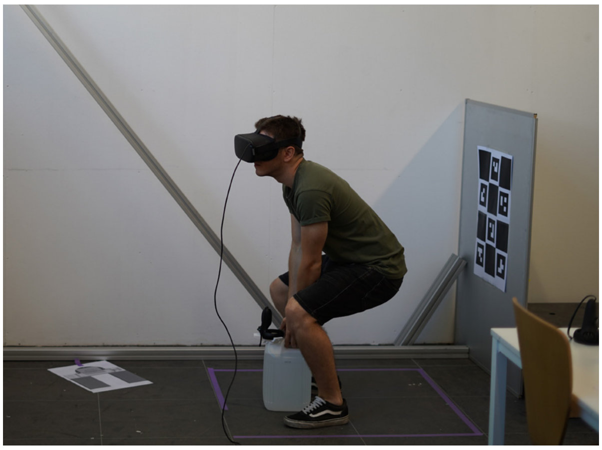


Figure 64.- Downward motion of the squat

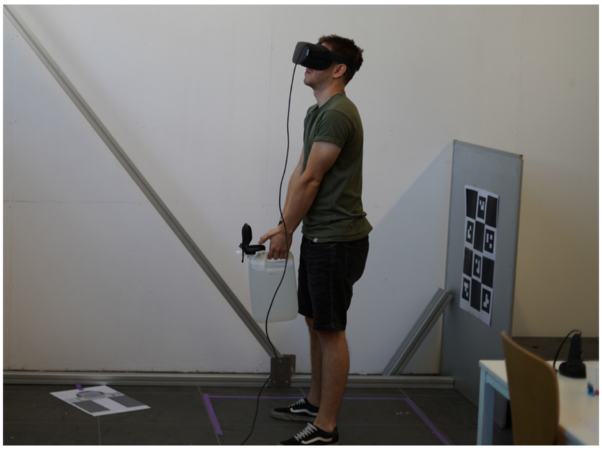


Figure 65.- Upward motion of the squat

Figure 66.- Participant filling the questionnaire

to obtain demographical statistics. The full experiment protocol is included in *Appendix 3*.

7.1.2.1 Materials

A 3D printed support conects the water jug to the *Oculus Quest* right controller. This allows linking the water jug to a virtual 3D model of itself.

The computer used for running the experiment mounted a processor *Intel-R- Core-TM- i7-10750H CPU @ 2.60GHz 2.59 GHz* and a *GPU Nvidia RTX 2060*. The camera system made use of an integrated webcam of a *MSI GL7 Leopard* and the back camera of a *Xiaomi Redmi S10*.

The experiment area is a 1.5m x 1.5m zone, marked with purple tape on the floor. The sizing is defined according to the *FoV* covered by the two cameras.

As previously anticipated a digital questionnaire is provided to the participants. It contains 5 different sections relative to each experiment, the comparison among them and demographics.

The questions seek to assess participants' perception of the feedback regarding the following factors: **understandability, usefulness, performance, posture correction, general engagement, confusion and criticism.** In order to evaluate so, Likert scales and the PrEmo tool are used (Desmet, 2018).

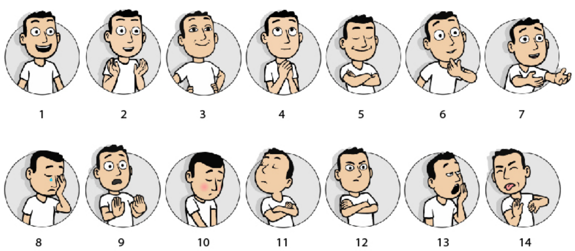


Figure 67.- PrEmo tool

Lastly, the experiment order is randomized to prevent biased answers due to the inevitable comparison we, people, perform unconsciously.

7.1.3 Participants

16 participants, aged between 21 and 30 years, provided written consent to participate in this experiment. 13 of them were frequenting a gym at least occasionally, whereas 7 played video games with the same frequency -considering occasionally 3 times a month-. 5 out of 18 participants were both into gaming and fitness, and, lastly, 1 sole participant did not do either.

Besides that, all participants had prior *VR* experiences.

The participants are recruited by word to mouth, considering those people that could be potential early adopters, according to the JIP team's study.

7.2 Results

This section gathers the results on the experiment which try to shed light on the research questions included in *Section 7.1.1 Research questions*. The results are divided depending on the nature of the information presented. First, the ones derived from the questionnaire relative to participants' perceptions are included. Lastly, results concerning performance are presented.

7.2.1 Perception

7.2.1.1 Experiment 1

Looking at the results from the PrEmo tool for Experiment 1 the most picked illustration was number 6, generally described as "***engaging***" or "***curious***", as shown in *Figure 68* .

There is a significant negative relationship between the visual feedback offered in Experiment 1 and the level of *understandability*, *confusion*, *performance*, and *posture* -*See Figure 71*-. However, there is not a common opinion among the participants. Quotes as: "***The screen with the green and red lines is confusing and it didn't help me***" and, conversely: "*With the coloured bars,* ***the score seemed less random****, so I actually wanted to achieve a high score*" are collected. The participants that report negative feedback consider the **perspective** as the reason why they cannot virtually align the water jug and the coloured canvas. At this point, the design of a simple 2D feedback element that does not provide users with their positional reference on that element itself is understood as a solution **hard to interpret**.

The perspective problem together with the fact that participants did not receive additional information on whether they were moving too low or high emphasized this last issue.

In general terms, Experiment 1 received the lowest score, obtaining an average of 2.78 points, far beyond the 3.14 and 3.51 points average of Experiments 2 and 3 respectively. However, there are not enough evidence to state that supportive visual feedback will not improve safety and perception. What it can be drawn from the experiment is that this specific solution did not obtain favourable results among the three experiments.

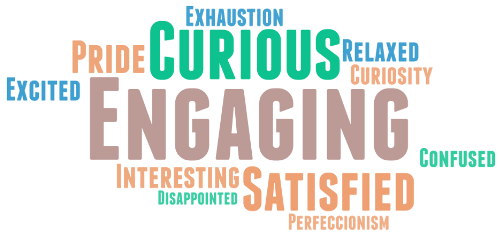


Figure 68.- Word cloud formed with the words used to describe the general feelings experienced in Experiment 1

7.2.1.2 Experiment 2

Regarding the results obtained using the PrEmo tool for Experiment 2, the illustration 5 is the most picked one, described as "***interesting***" and "***curious***", as shown in *Figure 69*.

Due to the fact the Experiment 2 - including statistics- **does not provide with exact information on where the user fails**, they tend to **change their general performance after receiving feedback**. One of the participants echoes this situation reporting: "*I was getting very low punctuation but* ***didn't really know how to improve***". Both the fact that the feedback is not immediate and users tend to forget their previous performances hinder the usefulness of the feedback.

At the same time, Experiment 2 makes participants feel the most criticized, although nobody explicitly reported this feeling. Additionally, participants perceived Experiment 2 as the best alternative in terms of "*performance*" and "*posture correction*", which most likely derives from the **conscious learning** that it promotes.

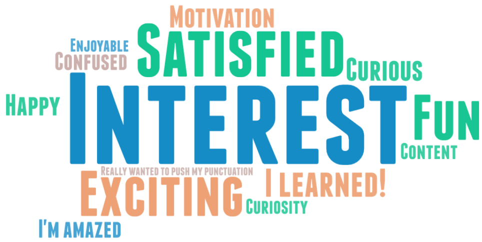


Figure 69.- Word cloud formed with the words used to describe the general feelings experienced in Experiment 2

7.2.1.3 Experiment 3

Concerning Experiment 3, illustrations 4,5 and 7 from the PrEmo tool are mostly selected, and used to express ***satisfaction*** and ***excitement***, as shown in *Figure 70.*

It is worth stressing that during the experiment, 9 out of 16 participants did not receive any pop-up message. 3 of these participants agreed upon the **negative impact** of "***the lack of guidance***" over the experiment.

For others, the fact that they **did not receive any feedback** was understood as a **synonym of success**, and reported: *"I nailed it. Good score" "I got a good score. And didn't go too high or too low"*

Although a considerable high rate of participants did not receive any pop-up message, the remaining 7 participants received an average of 1.74 pop-ups. These participants suggested that an **excessive amount of pop-up messages** could **negatively influence** the experience's **engagement**.

Conversely, the immediacy of the feedback is positively evaluated, letting participants perform better straight away.

Figure 70.- Word cloud formed with the words used to describe the general feelings experienced in Experiment 3

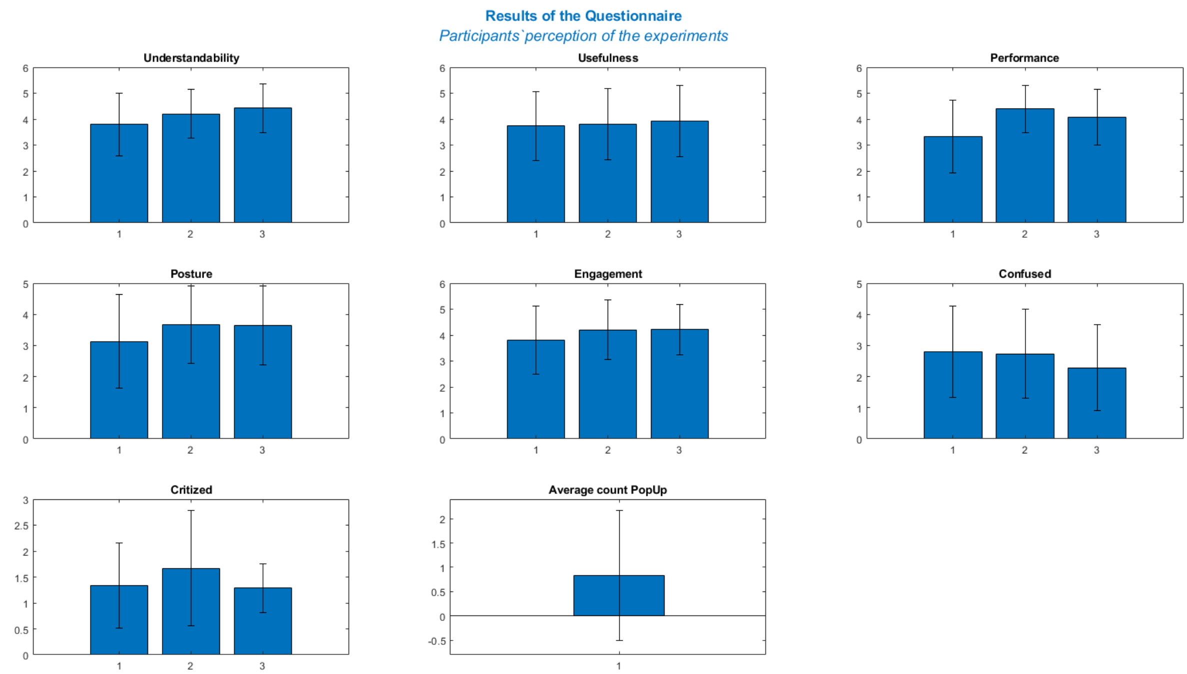


Figure 71.- Results of the Questionnaire. Participant's perception of the experiments

7.2.2 Performance

In order to assess participants' performances, the evolution of the water jug's height and back angle are recorded with a frequency of 4 times per second. These records are plotted as shown in *Figures 72, 73 & 74*.

These plots visualize: in the first place, the water jug's height for each of the experiments, being the green horizontal line the correct height calibrated for each participant, and the orange the upper and lower boundaries; and, in the second place, the back angle, being the black horizontal line the threshold that when crossed pops up the back injury risk message.

Three different plots are included and used to represent 3 different categories of participants:

Common Amateur: *Figure 72* visualizes the performance of a common user. Regarding the water jug height, it can be noticed how as some experiments progress the participant tunes their motion resulting in a better performance. Moreover, it can be observed how this participant acquire a bad posture in three occasions.

MoCap Ghost: *Figure 73* presents deviations on the back angle assessment, derived from poor MoCap effectiveness. This was caused by circumstantial limitations, such as brown pieces of clothing and dark wearables and bracelets.

Squats Pro*:* *Figure 74* shows the performance of a participant that regularly does squats supported by the guidance of professionals. After a few repetitions, they are able to tune their performance obtaining an average score above 85%.

Note that the correct height definition -shown in green- slightly varies not only for every single participant but also in each experiment -despite not being represented in the plots-, due to the fact that it is defined considering the eye's height given by the *Oculus* headset -which is positioned slightly different in each experiment-.

In addition, the average score per experiment is assessed -see *Figure 75*-. In general terms, Experiment 3 resulted in the best performance with an average exceeding 1300 points, out of the 2000 maximum reachable score.

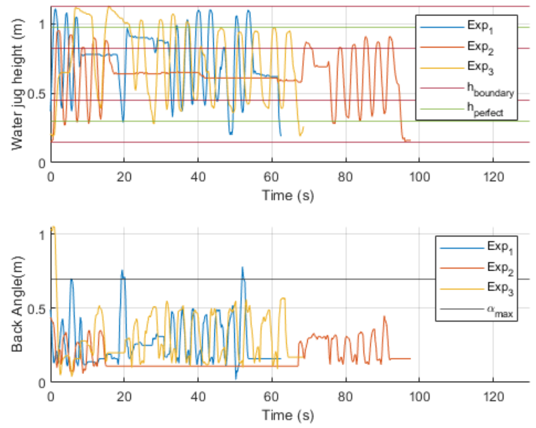


Figure 72.- Common Amateur. Graphs including the water jug height and the back angle for each of the experiments

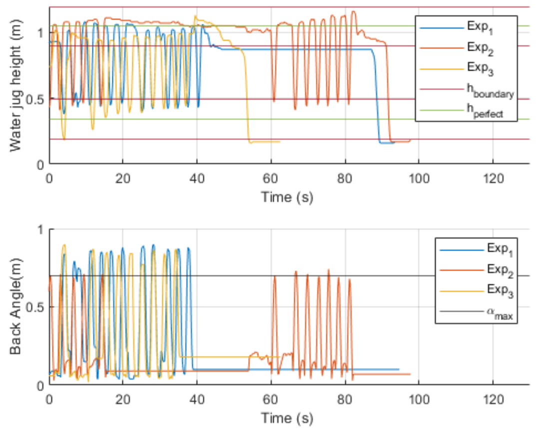


Figure 73.- MoCap Ghost. Graphs including the water jug height and the back angle for each of the experiments

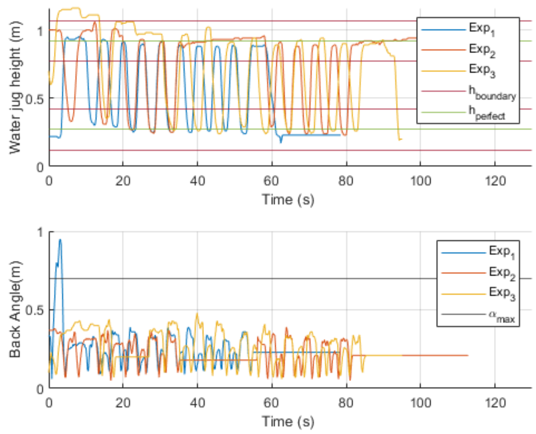


Figure 74.- Squats Pro. Graphs including the water jug height and the back angle for each of the experiments

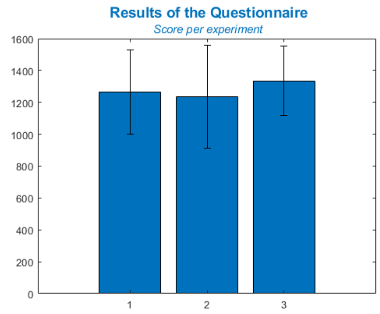


Figure 75.- Results of the Questionnaire. Score per experiment

Among other aspects observed during the experiment, each participant required a **different body posture due to its unique body shape**. In this context, rules-based models -as the one implemented- cannot provide the necessary flexibility to overcome the user's physical constraints. Therefore, as stated in *Section 4.1 Introduction,* to provide users with a unique experience out of the physical world limitations that constrain them Reinforced Learning based *ML* models are targeted as the most favourable solution. Thereby, users presenting heterogeneous physical conditions -from *weekend warriors, sedentary gamers and* people with physical limitations to elite athletes-, could compete among themselves.

Besides that, it was noted how the **duration of experiment varied** depending on the speed and technique of the participants. As an interesting remark, some of them stayed still waiting for the maximum score to appear and explored opportunities to hack the game.

As a last consideration to be noted, it has to be reminded that **neither the experiment nor the Ethereal Engine's envisioned interaction are hands-free experiences**. Under the experimented circumstances, closing a pop-up resulted complicate for the participants, who were asked to stretch their arm.

7.2.3 Results' discussion

This section is oriented towards providing significant answers to the experiment's research questions:

- **What is the desired tuning of a virtual trainer in terms of explicitness, immediacy, and strictness of the feedback?**

To successfully provide an answer, it is worth discussing the feedback alternatives first -getting a holistic perspective on the most tangible results- to consequently conclude the desired tuning of a virtual trainer.

The conclusions derived from each feedback alternatives are listed below:

- Visual feedback needs to offer users an accurate representation that could let them compare their performance with the desired situation. Otherwise, it would be a source of confusion and, eventually, disappointment.

- Statistics do not let the user know where they did something wrong, and they tend to change their general performance.

- Pop-up messages have a direct impact on the following action, however, their excessive incorporation reduces engagement.

- Pop-up messages change the state of the game to a pause mode. The statistic load experienced in this state hinders the interaction with *UI* elements.

Note that although conclusions on the specific solutions can be drawn, considering the big room for improvement in terms of the *UI* -including graphic design and elements' interaction- for all the 3 explored solutions it cannot be determined their full potential.

Once main conclusions from the different feedback alternatives are laid on the table, explicitness, immediacy and strictness are discussed:

- Regarding **explicitness**, it is important to think about **what information** is offered. In this case, for example, the visual feedback lacked information on whether the user was moving to high or low. Similarly, statistics did not tell users when they made mistakes and pop-ups just gave information in some extreme cases. Each of them offers certain benefits, which could be smartly combined to create a safe and engaging virtual trainer. However, none of these provided participants with a full picture to reach perfection.

- Concerning **immediacy**, participants positively assessed the immediacy of the feedback. In fact, including statistics -the least immediate solution-resulted in an increase in the **experiment duration** by an average of 62%. This fact could be both considered negative and positive. Since Ethereal Matter intends to provide intense workout sessions of approximately 45 minutes duration, it could either **slow down** the workout hindering the achievement of results or offer a chance to align feedback with **stretching and recovery intervals**.

- Reflecting on how explicitness and immediacy relate, immediate feedback should not be hard to interpret and game-related to boost the immersion. However, non-immediate feedback could help users to improve their general performance when they present bad habits.

- As an additional remark, **consciousness** emerges as a quality closely related to immediacy. The levels of consciousness presented in *Section 5.1 Concepts* were correctly assumed. Visual feedback promotes unconscious learning, whereas pop-up messages and statistics enable conscious learning, ordered in crescendo.

- Lastly, in terms of **strictness**, pop-up messages can be too restricting and might have a negative impact when they are used on excessive occasions. For high-risk situations, however, they are considered the best-suited alternative. Conversely, visual feedback happens to be the best solution to foster the application of the "*reward-punishment*" concept to enhance safety by inspiring users to acquire good posture -preventing certain bodily injury risks-.

- **How including a load in *VR* - in this case static- can have an effect on the interaction?**

Including a load in VR makes the workout more demanding, while keeping the experience engaging. However, the static load included in the experiment hinders the interaction with UI elements -e.g. buttons in pop-up messages-.

In this context, a gradual increase of the force feedback when switching from a pause state to a play state is considered an interesting opportunity to further explore.

- **How can we create a virtual trainer that would lead the user to self-correct their posture?**

Although the experiment only exhibits some basic functionalities of a virtual trainer, the participants' overall positive reaction demonstrates the projection of these digital products. Participants experienced the possibility of competing in *VR* while doing demanding gym exercises assisted with feedback that motivated them to change their performance. And, most importantly, they were satisfied and looking forward to repeating the experience right after.

Looking at the effectiveness of the virtual trainer, the back angle assessment succeed except when certain pieces of clothing- e.g. brown T-shirts and black bracelets- hindered the skeleton tracking. However, as previously stated rules-based models are too constricting, and are not **flexible** enough to adapt to the wide variety of users. In this context, **ML Reinforced Learning models** emerge as a promising opportunity to evaluate.

Another important detail to be mentioned is that there is not a clear answer on whether the headset height should be used to calibrate the system or not, since its position slightly varies depending on how the user puts it on and how well the ground floor is originally calibrated in the *VR* headset. However, it can be concluded that **calibration** offers an incredible solution to allow **fair competitiveness**.

Lastly, explicitly answering the aforementioned question, **the "*reward-punishment*" concept unconsciously integrated into games seems the most engaging way to inspire users to self-correct their posture**. Besides that **personal statistics** can be integrated for **recovery intervals**, and **pop-ups** offers a solution to warn users when **severe bodily injury risks** are likely to happen.

All these insights obtained from the experiment will be integrated in the design in the following section, converging in a final concept.

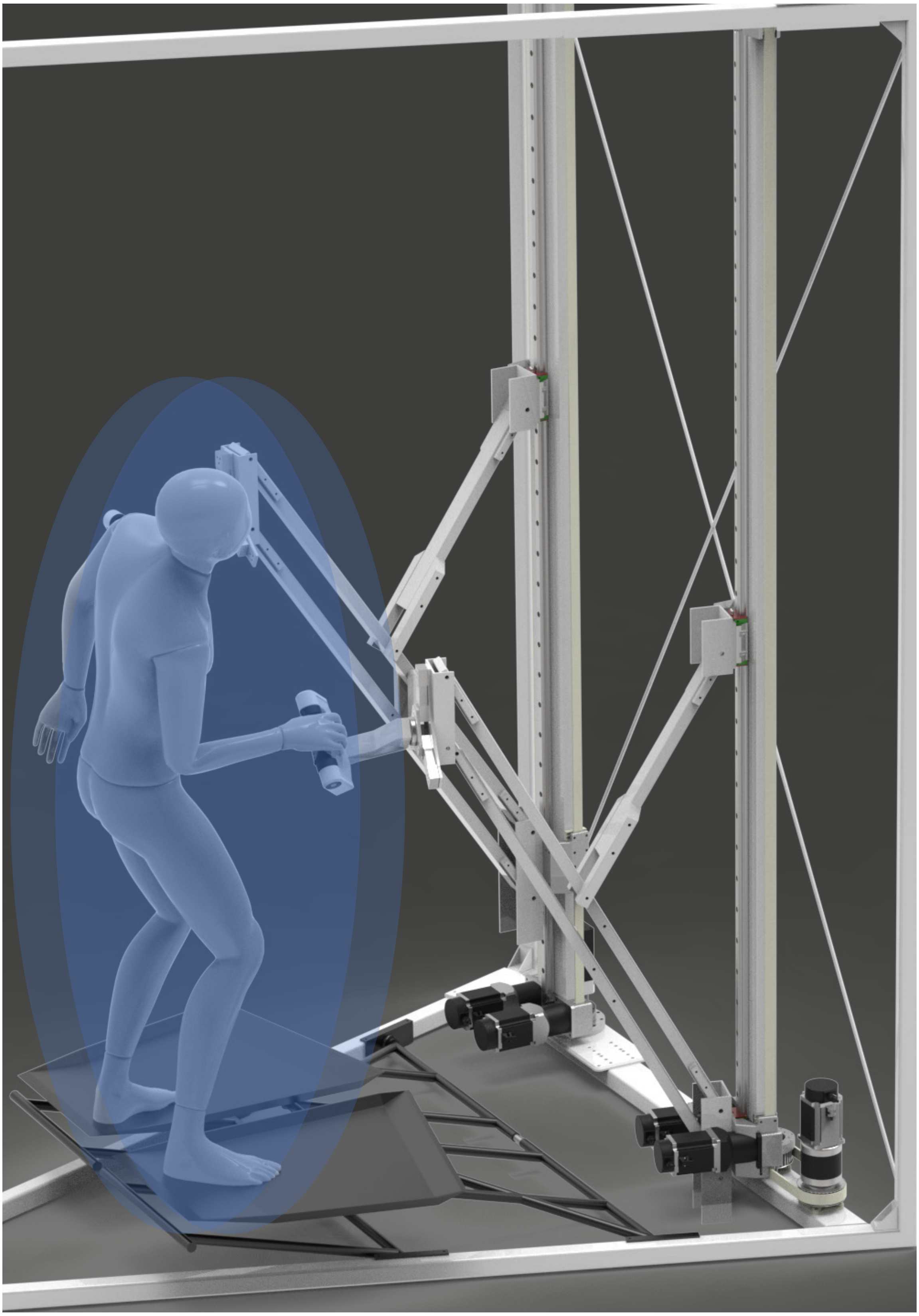


Figure 76.- Render of the envisioned *Delft Prototype* emphasising one of the limitations of the machine detected through this Graduation project: The user trying to access the keep out zone. (Lower carriage intersecting with the motors)

- C H A P T E R 8 -

Final concept

This chapter introduces the reader to the final concept derived from the Graduation project: *"the DelftV1 engine"*. It incorporates the main findings previously discussed -such as the fair competitiveness promoted by a calibration process and the inclusion of different feedback systems at different levels-, resulting in a final solution which enhances the experience by providing a virtual trainer that inspires users to self-correct their posture, and, subsequently, enabling a bodily injury-free experience.

Likewise, it introduces how the selected MoCap technologies already integrated into the prototype in Delft can be combined with computational models to maximize their performance.

8.1 Final concept solution

The following section presents the final concept derived from this Graduation project.

From the onset, this project wondered how a safer interaction could be provided while keeping the experience engaging -meaning fun, immersive and demanding-. By means of deepening the multiple areas that surrounded safety as a concept, it envisioned a system based on a virtual trainer that would self-inspire users to reduce the bodily injury risks present during the interaction with the Ethereal Engine. Different alternatives were designed, and simplified features were prototyped not only to test the system, but also to showcase the resulting system.

Due to the fact that the implemented technologies and prototyped system resulted into diverse effects throughout the interaction with the Ethereal Engine, the concept solution is presented together with *Figures 77 & 78* which offer visual support, letting the reader grasp the progression of the writer's intent.

The *DelftV1* system is the solution derived from this project. It proposes a motion capture system based on a multi-camera approach and an unprecedented interaction that promotes:

- **Fair competitiveness**, by adding an initial calibration process that adjusts the experience to each user's comfortable range of motion.
- **Safe interaction** by means of a virtual trainer that offers feedback at different levels including the right information to successfully exercise.

Regarding the **calibration process**, this is envisioned as the first action when entering the *VR* experience, and is merged with a warm-up session. It contains 2 different stages: *range of motion* and *force* assessment. During the first stage, the user is asked to perform certain free motion moves to assess their mobility range and tune the virtual experience accordingly. The *force* calibration offers a complementary calibration that not only helps to define the interval of load executable by the user, but also limits the range of motion of the machine restricting access to those positions in which the user could damage the armatures.

After completing the calibration, the position of the platforms and armature is adjusted to optimize the experience.

As briefly introduced, a multi-camera-based solution is implemented, in contrast to the depth camera-based system pursued in the US. Thereby, *DelftV1* not only offers an inexpensive solution to deal with occlusion, but also sets a new exploratory road and enables simultaneous intercontinental development of both alternatives. *MoCapForAll* is the software used in the prototype.

Additionally, the system considers the integration of a *Digital Human Modelling* module in order to tackle the main limitation of current multi-camera systems: the accuracy when it comes to defining a safety boundary surrounding the user. These modules by means of combining the anthropometric measures together with other user data -e.g. weight, sex, and body fat-generate a virtual replica of the user. The literature review spotted *DINED* platform of the Technology University of Delft and *MoSh* research from the Max Plank Institute for Intelligent Systems as promising advancements that could facilitate an effective MoCap. (Molebroek, 2018) (Black, 2014). These offer a solution for improving the immersion and reducing mismatch-related risks.

Additionally, to support the detection of different user categories -e.g. people in a wheelchair- a ML-based user category detection model reinforced with user's inputs is considered to be included. Thereby, before starting the *DHM* module the user category will be selected acceding to a different calibration according to users' needs. When *DHM* process is completed, the platforms and armatures are repositioned according to the user's data. Right after, the user translates to a virtual environment, such as *Horizon* from *Meta*. In that scenario, the user, through a digital menu, can either access predefined workout sessions or find their *ornithopter* to fly around anywhere in the *VR* world.

For new users experiencing the *DelftV1* for the first time, a tutorial brings them the chance to catch up with the operating system of the *ornithopter* or any other cool machine. In this case, the user assistant is visualized as a robotic drone that keeps you safe along your first wing-beats.

Right after, the user is ready to enjoy the experience while certain safety mechanisms running in the background and resulting in a **virtual trainer** keep them safe. Note that this system does not necessarily need to take a human shape, in fact, it can be smartly integrated, helping to consolidate the immersion.

The virtual trainer makes use of the data obtained from the MoCap system, and provides users with feedback, reducing the bodily injury risks. Considering the novelty of such systems applied to demanding force feedback training, the *DelftV1* blazes a trail for breakthroughs by incorporating the results obtained from an experiment that deepens how the tuning of the feedback regarding explicitness, immediacy and strictness can positively affects the user interaction -described in *Chapter 7 Evaluation*-.

Figure 78 illustrates how the feedback is meant to be integrated into the experience and is explained below.

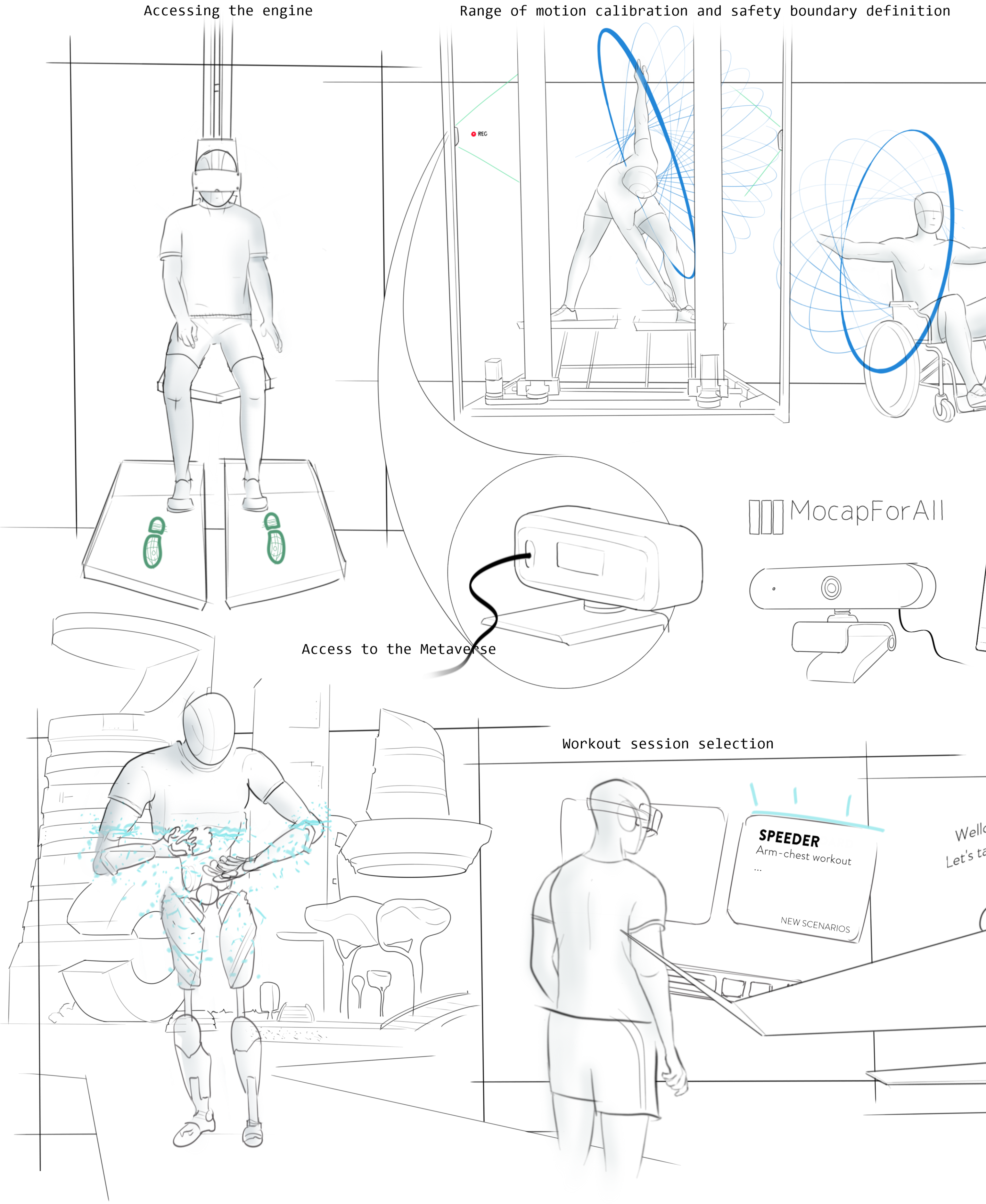
- **Visual feedback:** It is meant to frequently be included throughout the gaming/exercising session when risks that can derive from bad exercising habits appear -e.g. an incorrect posture-. It promotes unconscious learning, avoiding possible breakages of immersion resulting from requiring excessive attention to posture-related details. It offers the users visual cues letting them have a reference to compare with. It inspires users to self-correct their posture by means of a *reward-punishment* concept. In other words, by offering rewards that boost the experience - speed boost, higher scores, etc.-.

- **Pop-up messages** are targeted as a necessary element to warn users when risks that could result in severe injuries are likely to happen. Bystanders entering the exercising area, bad performance -resulting in *game over*- and excessive physical exertion are considered as situations in which a pop-up message would be necessary to inform users about the need of blocking the experience due to dangerous circumstances. The blocking will be conducted gradually by reducing the force towards free-motion. Their use is limited to exceptional cases avoiding users getting overwhelmed and worsening the user perception of the *DelftV1*.

- **Statistics and post-workout tips** enable optional conscious learning for those users who really care about their performance. Regarding the moment to include this type of feedback, it is envisioned to coincide with recovery and stretching intervals to give the user time to assimilate the learnings. As shown in *Figure 78*, recordings of previous exercises together with some tips to improve performance are included. In addition, the user's postural habits are visualized, showing off the potential of the motion capture system applied to tracking of workouts.

Finally, during the post-training feedback some questions to evaluate the suitability of the exercises to the user's capability are included. As physical therapists do with pain scales, this process will help the system to retrieve additional user data to tune the experience according to the user's capability and solve possible imbalances derived from the calibration. This does not necessarily mean that the calibration will present technical errors, however it has to be considered that each user could decide to put themselves to different limits while calibrating resulting in a different tuning.

By applying feedback at different levels the virtual trainer boosts safety while keeping the experience engaging. Considered as a valuable but also necessary add-on, it is already having an impact on the interaction design of the *DelftV1* and its further development emerges as a unique opportunity for future teams to bring the Ethereal Engine to the next level.


Accessing the engine
Range of motion calibration and safety boundary definition
REC
MocapForAll
Access to the Metaverse
Workout session selection
SPEEDER
Arm-chest workout
...
NEW SCENARIOS

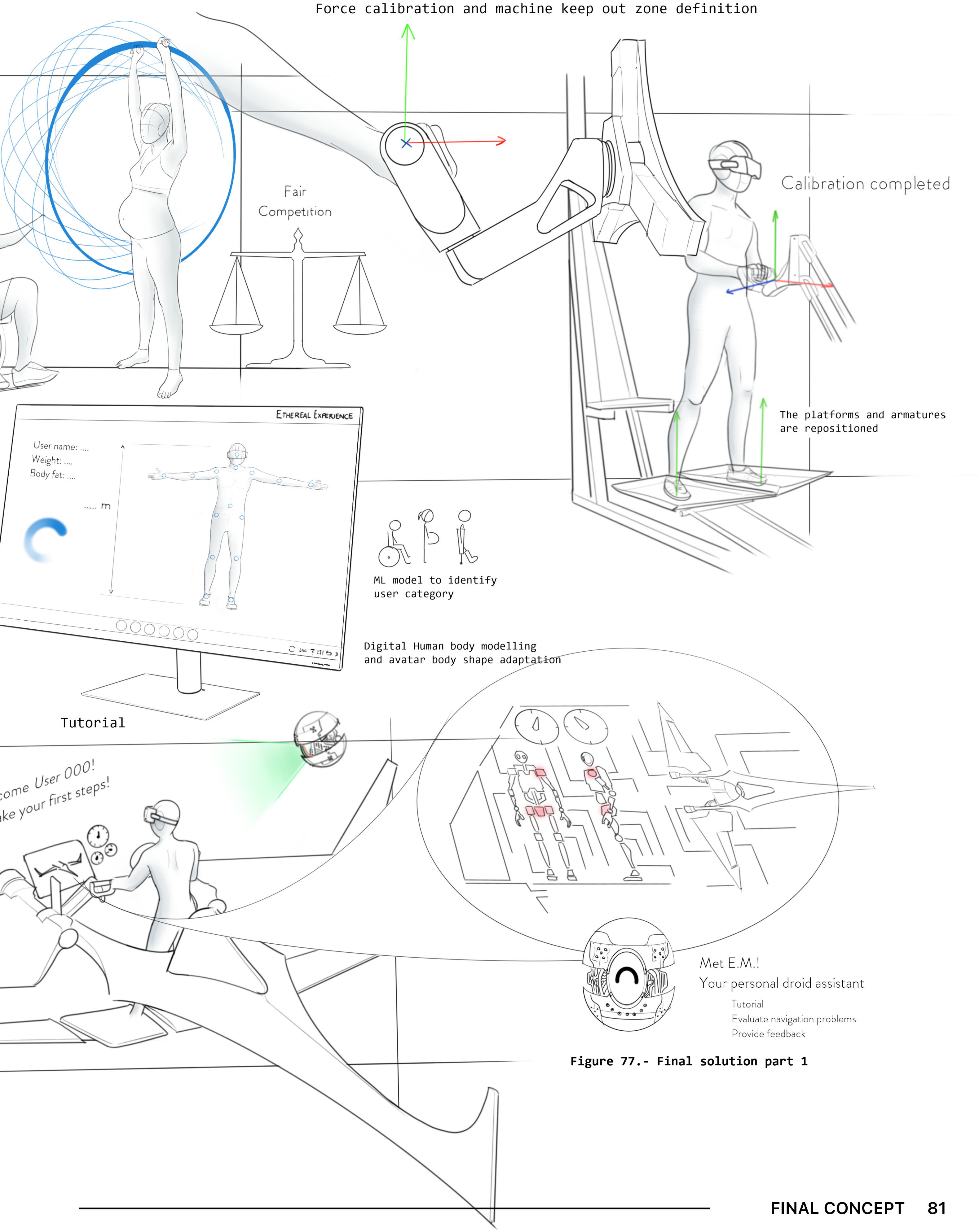


Figure 77.- Final solution part 1

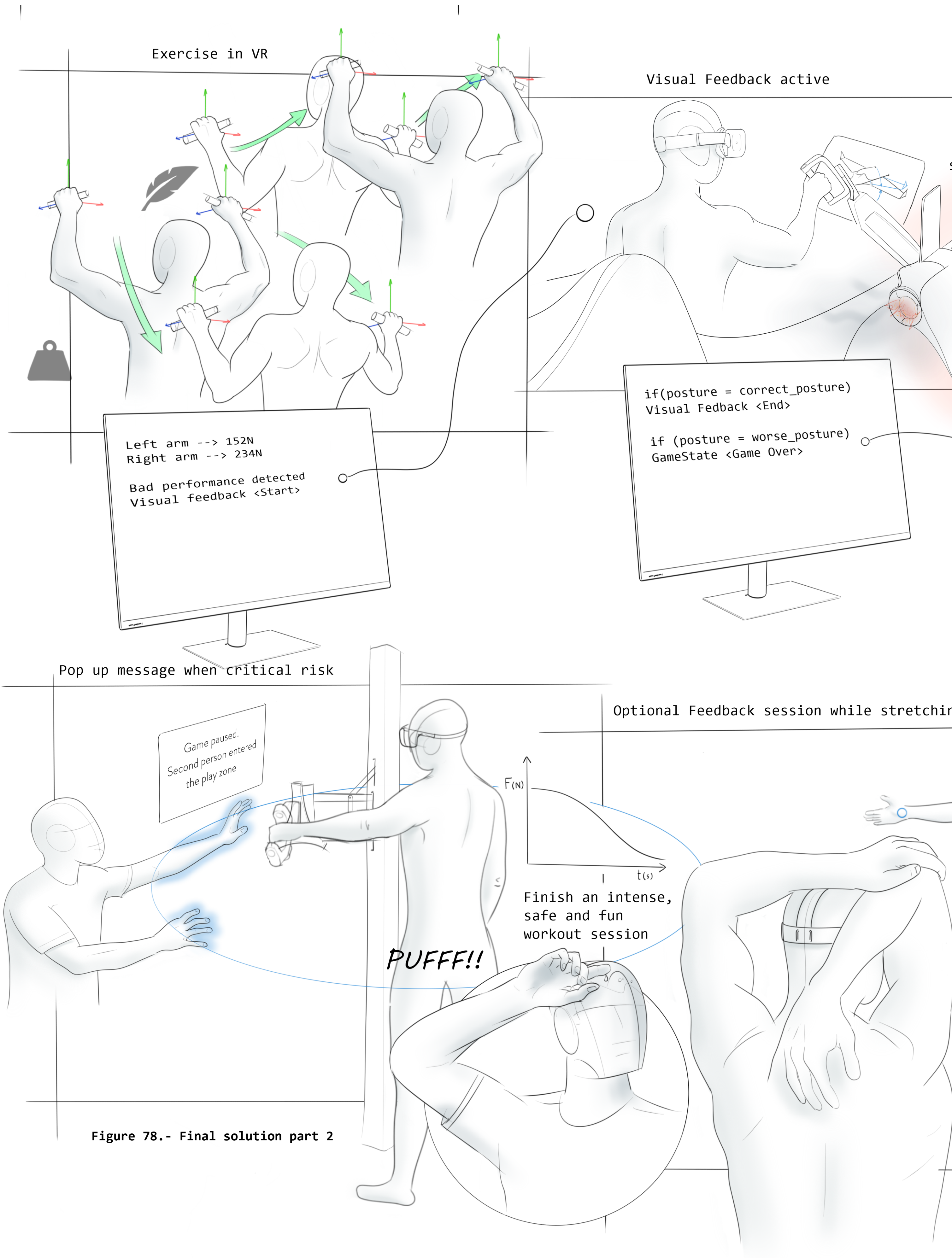
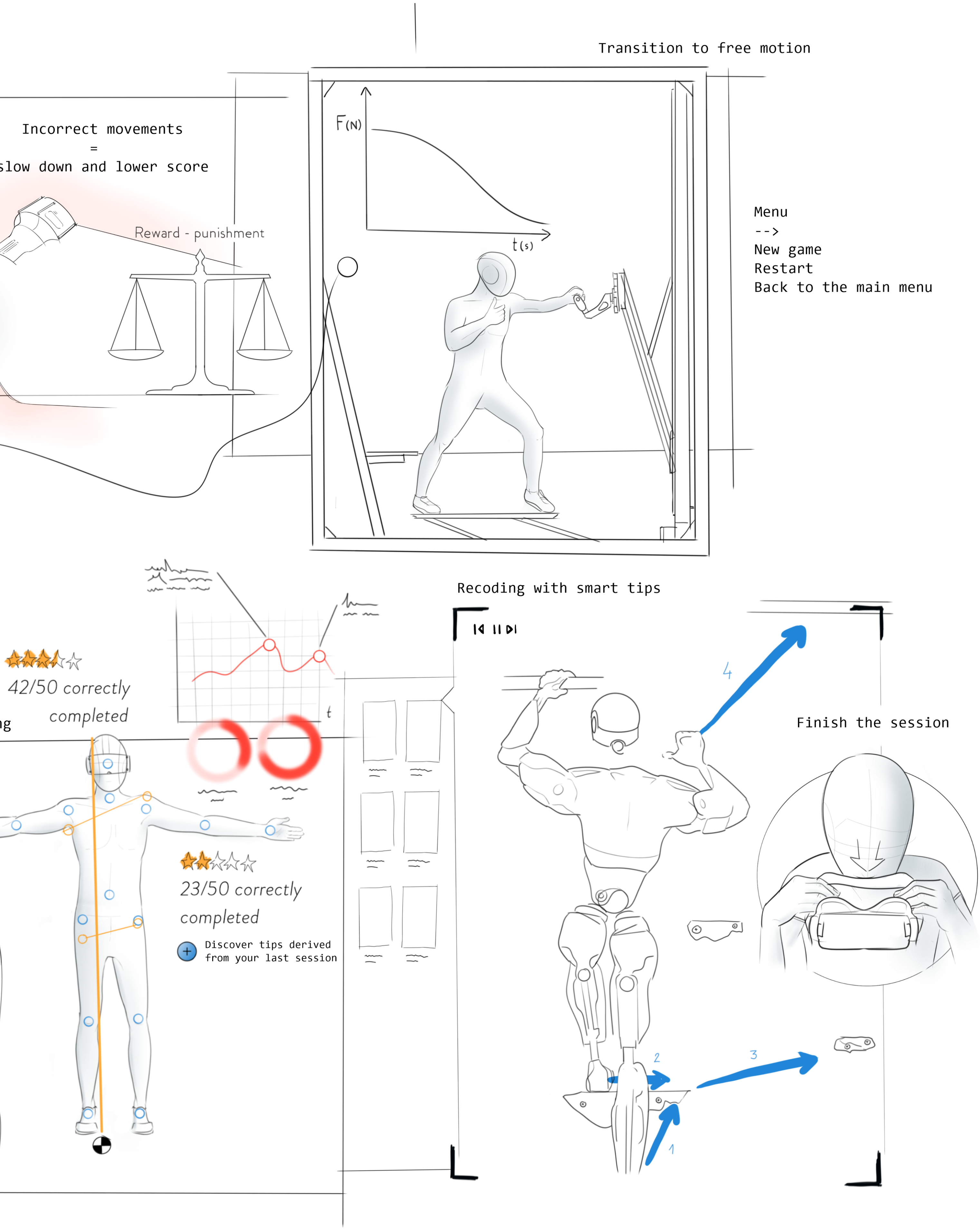


Figure 78.- Final solution part 2



Transition to free motion
Incorrect movements
=
slow down and lower score
Reward - punishment
F(N)
t(s)
Menu
-->
New game
Restart
Back to the main menu
Recoding with smart tips
42/50 correctly
completed
t
23/50 correctly
completed
Discover tips derived
from your last session
Finish the session
4
2
3
1

Figure 79.- Moritz and I, Alejandro, posing for the first time with the armature in its vertical position with a temporary fixation to the frame.

- C H A P T E R 9 -

Recommendations & reflection

This chapter includes the recommendations for both the client and future teams in Delft, to further develop the Ethereal Engine. It not only reflects on the successes but also includes the failures, with the ultimate goal of saving time for future teams in their way to understand, develop and manufacture such a multidisciplinary and exciting machine.

Additionally, a reflection in my performance along the graduation project is included.

9.1 For the client

This section incorporates the knowledge derived from this Graduation Project considered most valuable for the client, shedding light on aspects that being integrated would enhance Ethereal Engine's safety.

9.1.1 Bodily injury risks

Along this Graduation project, different risks are detected and categorized into **collision, posture, balance loss and long-term exposure**-related risks.

The opportunity to **reduce these risks by means of inspiring certain behaviour** in the game emerges as an important takeaway. By rewarding correct behaviours -e.g. correct posture, centre of gravity located between feet- or by punishing incorrect ones - e.g. repeatedly getting close to the keep out zone- we could have a positive effect on users' instant behaviour and, subsequently, in their habits.

Regarding collisions, there are plenty of solutions that can be extrapolated from current co-robots in industrial environments. In most cases, this risk is tackled by **defining a safety zone surrounding the user and robot** presenting a certain margin. From the performed research the current most promising alternatives make use of **encoders** for delimiting the robot's boundaries and **MoCap** for the user's. Likewise, the *ISO / TS 15066* is spotted by several authors as a guideline to define a collaborative robot safe interaction and could be a valuable source of information once the Ethereal Engine is close to being released in Europe.

Concerning balance, keeping the platforms visible in *VR* would reduce the risk of stepping out of the platforms. Moreover, it is observed how current studies agreed upon the fact that visualizing parts of the robot in *VR* increases perceived safety.

Additionally, several risks related to the *Ethereal Engine* are not necessarily easy to understand while you are in *VR* -e.g. keep out zone, and interaction with bystanders-. Therefore, by means of a visual interface these risks should be communicated to the user letting them understand why their experience is being limited.

9.1.2 MoCap

The implementation of a **multi-camera-based MoCap solution in Delft** sets an alternative path of development for this intercontinental collaboration project. Not having a clear answer on whether depth cameras or multi-camera-based systems, this decision offers Ethereal Matter an opportunity to develop in parallel both systems and compare results.

In any of these cases, it is considered necessary to implement a ***Digital Body Modelling*** procedure to adjust the virtual avatar to the user's size. This not only would reduce the mismatch but also would help users keep track of their real position avoiding collisions.

For the great majority of users, through a calibration process that would gather the skeleton data, weight and executable force a realistic representation of the user could be obtained. As the most promising examples, *DINED* platform of the *Technology University of Delft* and *MoSh* research from the *Max Plank Institute for Intelligent Systems* are detected. However, for exceptional cases -such as pregnant women and reduced mobility users- it is considered to implement an *ML* user category classifier based on images at the beginning of the calibration process. Users would be asked to confirm the categorization, reinforcing the *ML* model with their answers.

It is remarkably interesting how **calibration could be used to adjust the range of motion required**

in each game to users' motion capabilities. This discovery is understood as a unique opportunity to enable **fair competitiveness**, offering a chance to overcome the physical world constraints and letting anyone be a master.

Lastly, regarding the implemented software -MoCapForAll-, it allows the use of several cameras which can be calibrated one single time once they are permanently mounted in the frame, reducing the set-up time. Moreover, a solution to correct the relative alignment between this software and the Oculus headset is found and described in *Section 6.2.3 MoCapForAll implementation in Unity*.

9.1.3 Virtual trainer

Virtual trainers are a niche, and the fact that the Ethereal Engine can accurately measure force enables a unique and ground-breaking opportunity to develop these systems to the next level.

Moreover, virtual trainers emerge as an opportunity to motivate and inspire a safer interaction, by tackling the bodily injury risks by starting from the users themselves. Thanks to the "*reward-punishment*" concept -derived from gaming disciplines- users could find unconsciously a motivation to exercise in a safer way.

This concept could be incorporated by linking the score, speed or any other incentive to the correctness in terms of posture correction, balance, distance from the keep out or any other risk avoidance.

Likewise, through this graduation project, the applicability of different feedback alternatives -visual cues, statistics, pop-up messages- to the *VR* experience is studied and tested with users, providing Ethereal Matter with insights on where each of these could be integrated and the values each of them promotes -e.g. conscious *vs* unconscious learning or immediate *vs* post-workout feedback-.

It is worth mentioning that the application of these systems has not presented a negative impact on the engagement of the overall experience, in fact, feedback kept experiment participants willing to continue exercising, although they were doing squats.

Chapter 8 Final concept elaborates on the suitability of each feedback to the different stages of the interaction presenting my personal conclusion after a year of working on the engine on how Ethereal Matter could have a positive impact on the current social VR technology development.

9.1.4 Others

As another conclusion derived from my interest in the recent advancements in the VR industry, VR metaverses -like Horizon from Meta- are likely to change how we understand the intro-outro transitions from games. You could access different games/ workouts through the same platform. Considering the fact that the Ethereal Engine is meant to be a workout platform it could be worth taking a look at how the transition from initial menus to actual games is designed, and if this is strictly necessary.

9.1.5 Delft Engine

As the last contribution, I would like to include some personal conclusions obtained from the intercontinental development.

Firstly, it has been an immense pleasure to work for Ethereal Matter, where Scott has always provided us with the necessary information and his creative and effective mindset in order to build a working prototype. The communication through Discord turned out to be really beneficial to establish an ongoing repository of the project's knowledge.

Secondly, regarding CAD files we took some details for granted, that almost ruined some of our CNC pieces. In the lower mount, there were some holes that weren't symmetrically placed. Although not seeming like a big issue, it could have saved us a few instants of panicking to know that CAD models are still ongoing files presenting these inconsistencies.

Lastly, one armature's mechanical assembly is ready, which means that if the next JIP team continue with the electronics and power supply mounting the first intercontinental handshake in the Ethereal Engine could be a reality by the end of the year.

9.2 For future teams

During this graduation project, I have learnt how keeping this project going is not all roses and unicorns. It worth keeping in mind that in such an innovative project many bottle necks can be experienced and dead-end roads can be reached. However, as engineers we need to demonstrate flexibility and adaptability to overcome failure while keeping a right balance between theory and practise.

Next, I include some of my tips for future students that are willing to make a difference in the Ethereal Engine's development.

Project management

Regarding project management there are a few aspects that could be beneficial to have in mind for achieving a successful project:

- Define your expertise areas and make the most of your knowledge. Accept that you will not fully understand the machine by the end of the first week.
- Do not reinvent the wheel. Make use of the resources at your disposal and ask previous teams.
- Try to implement your conceptual changes over the prototype. Building a whole prototype from scratch takes ages.
- Keep the right balance between theory and practice. Combine theoretical development with partial prototypes.
- Involve the stakeholders. Every person developing the engine will provide you with insights into the interdependencies of the design.

Project needs

I feel necessary to mention that as you will be working for a company in the university context, it will be challenging but also enriching to manage both stakeholders' needs. Next, I include some recommendations for the next actions that need to be done to get a fully working prototype in Delft:

- Keep the right balance between your skills, ambitions and the project's main need: achieving a first working prototype to showcase the *Ethereal Experience.*
- Work on the control system of the motors. This considers the integration of *Arduino* for the load cells and motor controllers linked to Unity.
- Regarding mechanical design, work on the *FEA* of the most developed system: US prototype. Update the *MatLab* force estimation model including the general sizing developments on the robotic armatures, and use those loads as an entry for the *FEA*.
- Remember that one of the main challenges of the *US* prototype is to optimize both cost and weight. There are plenty of components, such as bearings, motors, and gearboxes, that are really expensive; and studying the incorporation of cheaper solutions might be promising.
- Shock absorption and vibration are phenomena hard to assess considering the fact that the forces entering the system are hardly predictable and variable depending on the user. So far, little research has been performed in this area, which could be interesting to further study.

Manufacturing and orders

Probably, the most relevant consideration that will determine whether you can prototype your concepts or not is to have a good plan with 2-3 weeks of buffers. Besides that, by incorporating experts when it comes to set orders -e.g. Chris for electronic components, Erik for manufacturing materials- you will be able to contrast and verify that you make the right decision.

As a last tip regarding manufacturing, prepare technical drawings and double-check with at least two people before doing any machinery operation that could ruin a piece.

9.3 Reflection

After working for a year on such a revolutionary product in such an enriching environment, there are way too many comments, learnings and takeaways that I could include. However, there are some key points that I feel necessary to highlight due to the impact on my future engineering career.

Firstly, during this graduation project, I felt how my contribution played a big part in establishing the project in Delft. There were different parties involved -AED team, US company, our supervisory teams and Chris- and each presented different needs that I needed to fulfil -more academic or practical-. With the sand of the time, I got a clear idea of how to manage the stakeholders to make the most out of my project -speeding up the funds obtained, involving experts in technical decisions, and adapting my speech-.

Secondly, I worked on a complex engineering project that required interdisciplinary knowledge, accepting that there were certain areas out of my expertise but also knowing that by communicating with my workmates, we could integrally cover the diverse disciplines that the machine encompasses.

Additionally, I experienced the contrast between working in an academic or companies environment. Whereas in the university, correctness and logical procedures are prioritized over the speed of progress and practical solutions, in companies' environment, results are priority number one.

Related to that, together with my teammates, we found a way to fulfil the requirements of both interested parties through exploring different paths while establishing a minimum version of the prototype, which shared some functionalities understood as minimum requirements.

However, I also made mistakes from which I learned. Before midterm, due to the ease of fulfilling the auto-imposed project deadlines, I regularly met with both the chair and mentor, updating them on the state of the project. However, as soon as prototyping started, the project management got more chaotic, not paying enough attention to the information selection for clear communication.

Apart from that, critically thinking about the initial planning and assignment, the project brief was adjusted since the results obtained before midterm detected virtual trainers as a more complex solution than just applying an ML model, requiring several design actions to be done before starting thinking about its implementation. Besides that, estimating the duration of the amount of time for prototyping a system that merged motion capture and VR was not precise enough, resulting in 3 weeks of delay derived from difficulties in the coding script writing.

Lastly, it has been an immense pleasure to work for and with Ethereal Matter, where Scott has always provided me with the necessary information and his creative and effective mindset in order to build a working prototype. Moreover, I would like to thank Erik Tempelman and Jered Vroon for their guidance which has been incredibly valuable for learning how to tackle such an exciting challenge and communicate my progress to different audiences.

- C H A P T E R 1 0 -

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Figures

- C H A P T E R 1 1 -

Appendices

Development of a VR based robotic platform towards a safer experience

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 07 - 02 - 2022

04 - 07 - 2022 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Background:
During Q1 of the current academic course (2021/2022), I participated in the Joint Interdisciplinary Project, where I worked within a group of 6 engineers for Ethereal Matter, a US-based company that aims for a revolution in the fitness industry through a machine that combines Virtual Reality and a robotic armature that provides force feedback. The aim of the project was to set the base to generate a replica of a working prototype in the US, that would actively incorporate upgrades to optimize the product in terms of performance, weight, and cost.

The fully understanding of such a multidisciplinary machine reached by the end of the project, provided a more elaborated view of the challenges it would face when released to market. From these, creating a safe product together with boosting a safety perception over the user are highlighted.

By the time being, the safety measures are limited to a dead man switch implementation on the grip. This system detects the user releasing their hand from the grip and allows the user to escape the VR experience immediately in case of emergency. Despite the limited safety measures, the interdisciplinary team generated several resources that will be used in this project: a list of the possible applicable laws related either to human robot interaction or fitness, an assessment of possible sensors to track the user state, and a questionnaire related to the perception of the machine.

Project pitch
You work long hours in a corporate setting, counting down hours to 18:00, your hour of fitness. When you arrived at the gym, you step in your selected Ethereal Engine, put on your head set, and immerse. You glance down at your digital body and perceive an unusual weight moving your arms. You look at them and see a pair of wings. You give a strong upward press, followed by a solid downward pull, and you lift gently from the ground. You still are getting used to your new limbs, and suddenly you are dangerously about to lose your stability. A second later, you perceive some adjustment in the graphical interphase and feel how the machine is adjusting its behavior to keep you safe without exerting extra force. You feel relieved and continue enjoying the experience.

Stakeholders
This project is framed in a complex structure that brings different benefits to the involved parties. From the university side, Erik Templeman and Chris Verhoeven coordinate assignments related to the Ethereal Engine. These are: two Advanced Embodiment Design (AED) groups from the Industrial Design Engineering faculty, and a Next Generation Robotics group from the TU Delft Robotic Institute.From the company side, Scott Summit (founder and expert on mechanics and design) benefits from the students engineering work, conducting workshops in IDE Academy as payback. Apart from that, scrum methodology and weekly updates are adopted as a solution to keep track of the intercontinental progress. Additionally, Orson Rossetto is an additional figure from the company participating in those meetings for discussing any issue related to software and hardware.

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introduction (continued): space for images

image / figure 1: Ethereal Engine. Physical product

image / figure 2: Ethereal Engine. Virtual experience

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

When it comes to envisioning the desired robot-human interaction of the Ethereal Engine, three forces emerge as antagonistic but also necessary requirements to keep the user attracted. These are the realism of the experience, the enabling of intense workouts, and the physical health of the user. A balanced combination of these three key features would considerably help the users achieve their health objectives.

By the time being, from Ethereal Matter, the robot-human interaction design has been oriented towards the withstanding of the forces exerted by the user, prototyping a robust system. The proposed project aims at diving a level deeper into the design of an interaction that reduces the risks of getting injured while keeping the experience challenging and realistic. This problem will be tackled considering the use of the technologies already implemented on the Ethereal Engine (MoCap and user state tracking sensors) and focus on how to make the system understandable and safe.

Said that the spotted problem is divided into two subproblems:

1) Make Virtual World interaction safe in the real world
Can we make use of positional/force/virtual world data in order to avoid overstrain and bodily injuries? And if so, what is the desired human-robot interaction? Should it provide feedback through the VR interface, a physical response, or a combination of both? How should it be implemented?

2) Perception before getting into the Virtual World
How could it be perceived as an understandable and safe product? Could we sensorily motivate a safe first interaction (visual, sound, touch)?

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

I am going to improve the interaction with Ethereal Engine in terms of safety while keeping it challenging and realistic, by means of a system (physical product and data model) that enhances its perception and gives certain flexibility to the behavior of the Ethereal Engine when the user could get injured. Simplified functionalities of this system will be tested and prototyped.

The research will be focussed on 2 overlapping topics: Virtual World interaction, Perception before getting into the Virtual World. In the second place, an interaction that will provide a safer behavior will be designed. Finally, a data model will be prototyped and the concept implementation over the prototype will be presented and discussed.

1) Make Virtual World interaction safe for the real world
Select 3 possible activities/games of the Ethereal Engine, and prioritize one of these.
Explore postures that might provoke the user to get injured while exercising.
Explore how positional/force/virtual world data of the user could be used to enhance safety during the virtual world interaction and define a response of the machine that avoids the user getting injured. (Either physical or virtual)
Deliver a prototype of a model at least one of the activities/games that based on the recordings obtained from the MoCap system makes the interaction safer.

2) Perception before getting into the Virtual World
Design the frame deciding components positioning, elements to ease the interaction, and what to show and hide to be perceived as a safe product.
Deliver an argumentation of the reasons that motivated the design choices that claim to make the system be and be perceived as a safer product.

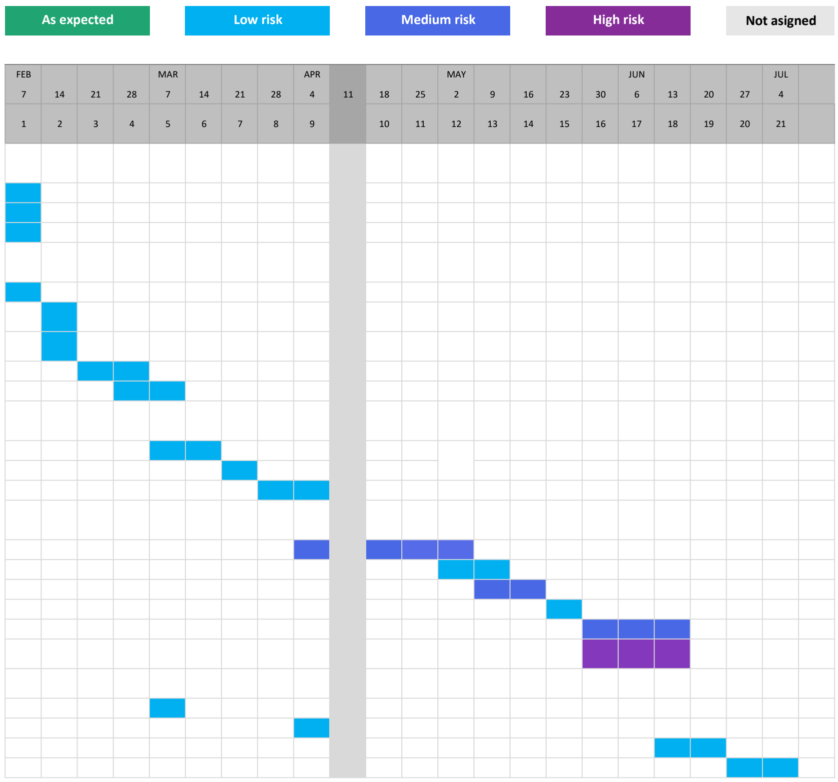
PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 7 - 2 - 2022 | 4 - 7 - 2022 end date

Kick off date:	07/02/2022
Midterm	08/04/2022
Green light	03/06/2022
Graduation	04/07/2022

Description of the task	Start date	Days
PREPARATION		
Kick of meeting	07/02/2022	0.5
Conversation with former developers	07/02/2022	0.5
Selection of activities	08/02/2022	2
RESEARCH		
What is the current system arquitecture?	10/02/2022	2
How does the current interaction work? What are its limitations?	14/02/2022	3
Which are the risky postures while exercising in the Ethereal Engine?	17/02/2022	4
How data can be used to enhance safety?	23/02/2022	4
List of requirements formulation	01/03/2022	4
DESIGN OF THE INTERACTION		
Concepts generation, sketching	09/03/2022	10
Concept selection	25/03/2022	2
Envisioned system interaction definition	29/03/2022	6
DEVELOPMENT AND TESTING		
Implementation on the CAD model	08/04/2022	10
Data adquistion: Set up the test and run it	03/05/2022	5
Data preprocessing: Find patterns	10/05/2022	7
Evaluate the data based model	19/05/2022	5
Rendering/Animations	27/05/2022	10
Testing perceived safety with user	13/06/2022	4
REPORTING		
Reporting stage 1	01/03/2022	2
Reporting stage 2	06/04/2022	2
Final Report	17/06/2022	10
Final Presentation	01/07/2022	7



The project flow will be based on a scrum methodology, dividing the process in different sprints. The duration of these sprints will differ from 2 to 3 weeks, in such a way that there are at least 2 sprint reviews per phase that fit the end of the diverging and converging processes (Weeks 2, 4, 6, 9,12, 15, 18).
Note that for the Development and Testing phase three sprints are planned, due to the importance of keeping a fluent communication in the stage that most of the technical difficulties related to prototyping could arise.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

This project is the culmination of my university journey, throughout I have developed my passion on multidisciplinary engineering projects. Back in in June 2021, when I first discovered the Ethereal Engine, two questions I formulated to myself got me attracted: in first place, how could such a complex machine work, and second, what was the future that this machine envisioned?

What I undoubtedly consider was his groundbreaking impact on shaping the new generations lifestyle. I believe I am right at claiming that technology is wrongly impacting our youth, both in physical and mental terms. I see my participation in the Ethereal Engine development as an opportunity to redirect society towards a healthier lifestyle. Moreover since I am considering to benefit from the user-state data to enhance the experience, my design proposal will reflect on the ethical issues that this kind of applications arises.

I decided to focus on the making the Ethereal Engine a safer product, since robot-human interaction is a social and technological cutting-edge matter that as a designer I want to help shaping.

Regarding the competences I want to prove, I would highlight machine learning and computer sketching from my elective semester. Apart from that, I will continue developing my personal design expertise in CAD design, systems engineering, user interaction, programming and rendering, that considerably influence my approach.

Other ambitions are listed below:
- keep track of the project evolution and implement Scrum methodology until the end of the project.
- collaborate with the other people involved in the project, resulting in solutions that are compatible and enhance the overall performance of the Ethereal Engine.
- deliver a model that is considered by the company to be further developed and implemented on the Ethereal Engine.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Table D.1: List of Requirement

ID. Code	Name	Measurement Criteria	Challenges Involved
ME-001	Armature Structural integrity	Maximum force along z : 1300 N for 1 armature. Maximum forces along x and y : to be defined	Industrial Design + Manufacturing
GR-002	Maximum weight of the user	130kg	Power Management,Manufacturing
SF-002	Escape the virtual experience	Ensure immediate shutdown of the engine	Virtual Immersion,Deadman switch, Laws & Regulations
MK-002	Target clients	The product can reach the market with a competitive or appealing selling price. Current prototype price: $18K; selling price x3: $48K	Marketing
UX-005	Improve MoCap accuracy and reduce occlusion	Resolve current occlusion problem while having reasonable accuracy	Virtual Immersion + MoCap
SF-001	Fulfil the applicable legislation	Applicable legislation in robots, assistive machines, fitness equipment	Laws & Regulations
EL-002	End effector position tracking	Reduction of occlusion from armatures and sensors and ensure accurate end effector tracking	Position Tracking
UX-004	Size the forces according to the user	Give cues in the right forces of the machine and calibration opportunities	Human Range of Motion
GR-001	Maximum speed of the end effector	From the 11m/s user maximum speed, the machine is limited to 2m/s belt speed	Power Managment, Manufacturing
GR-003	Build a partial prototype to set the base for further development.	Functioning of some of the functionalities. Mechanical system prioritised	Industrial Design + Manufacturing
UX-003	Minimum intrusiveness of MoCap system	Markerless capture system	Virtual Immersion + MoCap
UX-001	Keep out zone reduction	Reduce the current keep out zone. Diagrams	Human Range of Motion
ME-004	The system has to be light weight but stiff	Reduction of the weight while maintaining or reducing the bending of the armature.	Industrial Design
UX-002	Size the machine according to the user	Give cues in the right dimensioning of the machine and calibration opportunities	Human Range of Motion
EL-001	Optimize the power consumption	Reduction of current overall power consumption	Power Managment
UX-007	Intro-transition design	Improve current solution. Involve user in the assessment	Virtual Immersion
UX-008	Outro-transition design	Improve current solution. Involve user in the assessment	Virtual Immersion
UX-009	User state tracking to ensure users' well being	Measure vital signs of the user with reasonable accuracy and minimum intrusiveness	Tracking devices
UX-006	Prevention of motion sickness	Reduction of mismatch between visual inputs and vestibular inputs; reduction in latency	Virtual Immersion + MoCap
MK-001	Target users	The solution is rated as appealing and catch users' attention in a positive way	Marketing

Continued on next page

Table D.1 – *continued from previous page*

ID. Code	Name	Measurement Criteria	Challenges Involved
ME-003	Frame disassembled dimensions	The frame has to be able to get through an industrial door	Industrial Design
ME-002	Frame Transportability	The frame has to fit in a ban able to be driven with conduction permit B	Industrial Design

Experiment Protocol

Experiment Introduction

- Brief explanation of the Ethereal Engine
- What is the aim of the research?
  - How different feedback alternatives affect the game performance
- Experiment setup
  - The experiment consists of 3 different sections in which you will experience different feedback alternatives.
  - Your personal objective: Do 10 squats while lifting a water jug.
  - You will receive a certain score from 0 to 100 per upward or downward movement for each squat.
  - The score per motion will appear in front of you every time you complete an upward or downward motion.
  - The total score will be included in a menu you can show on your left.
  - The score depends on the vertical displacement of the water jug and body posture.
  - By participating in the experiment, you will enter a competition for a cake.
  - Different feedback elements will appear trying to help you to perform better in the game. I will explain each of them before each of the section of the experiments.
  - Experiment area.
    - Marked with purple tape
    - What happens if you leave the experiment area?
  - I will be keeping track of your progress through my laptop, helping you to interact with some elements.
- Consent
  - Give the questionnaire. Tell them to read and click next for giving consent.
  - As an important remark, abstain for participating in the experiment in case you ever suffered an epilepsy episode
  - Positional data will be recorded, but it is completely anonymous.

Introduction VR

- Help to put the VR headset
- Explain the systems misalignment.
  - MoCapForAll and Oculus Quest coordinate systems are not aligned by default, and these are misaligned most of the times user's take the headset off.
- Experiment the boundaries
- Calibrate
  - Open your arms, and I will start the calibration process. We get your anthropometric data to adjust the experiment to your range of motion.
- Any questions?

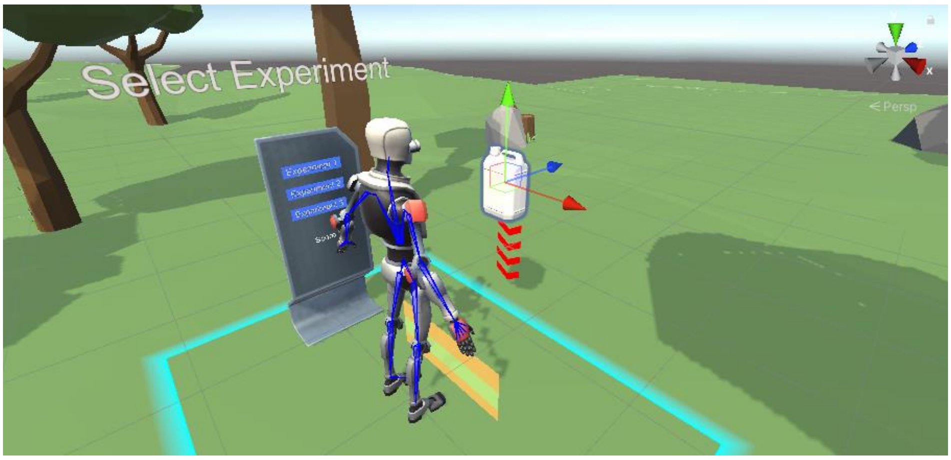
Experiment X

- Select Experiment X
- Explain feedback
  - In all the experiments in case it is necessary you will receive feedback to correct your posture.
  - Green and orange panels that indicate the place you need to displace the water jug. Remind them that green is better that orange.
  - After 5 repetitions you will receive feedback on your performance to potentially improve.
  - If you get excessively high or low, you will see a pop-up message
- Get participants into starting position
- Get the water jug
- Go!

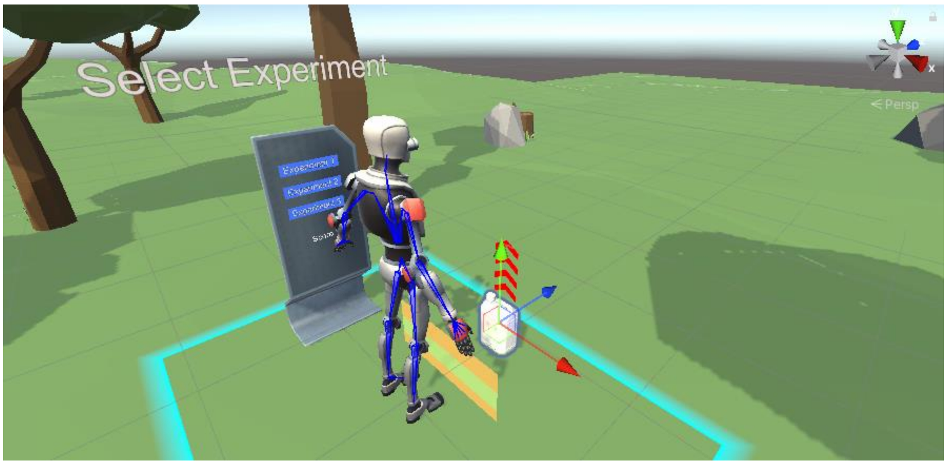
- **Record score**
- Remove headset

Questionnaire X

- Explain questionnaire's procedure
    - Speaker notes: Along the questionnaire, you are going to be asked to return the questionnaire, so I can select the order in which you followed the experiments.



Arrows communicating that the user needs to move the water jug downwards



Arrows communicating that the user needs to move the water jug upwards

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

//Robot Kyle Rig
//Script used to create a UI tool that links the data retreived from MoCapForAll to Robot Kyle.

[System.Serializable]


public class VRMap
{
    public Transform vrTarget;
    public Transform rigTarget;
    public Vector3 trackingPositionOffset;
    public Vector3 trackingRotationOffset;

    public void Map(GameObject Offset,float headRotation, GameObject Camera) //Including position and rotation here the value keeps along the time
    {
        //Update the position of certain node of Robot Kyle to match the position retreived from MoCapForAll + include manual offset if desired
        rigTarget.position = vrTarget.TransformPoint(trackingPositionOffset);
        //Update the rotation of certain node of Robot Kyle to match the rotation retreived from MoCapForAll + include manual offset if desired
        rigTarget.rotation = vrTarget.rotation * Quaternion.Euler(trackingRotationOffset);
    }
}

public class MoCap : MonoBehaviour
{
    public VRMap hips;
    public VRMap ribs;
    public VRMap neck;
    public VRMap head;
    public VRMap rightUpperArm;
    public VRMap rightForeArm;
    public VRMap rightHand;
    public VRMap leftUpperArm;
    public VRMap leftForeArm;
    public VRMap leftHand;
    public VRMap rightThigh;
    public VRMap rightKnee;
    public VRMap rightAnkle;
    public VRMap leftThigh;
    public VRMap leftKnee;
    public VRMap leftAnkle;

    public Transform headConstraint;
    public Vector3 headBodyOffest;
    public GameObject Camera;
    public GameObject ControllerLeft;
    public GameObject ControllerRight;
    public Vector3 offsetRotation;
    public GameObject Offset; //gameobject
    public GameObject CameraRig;
    public GameObject Head;

    // Start is called before the first frame update
    void Start()
    {
        //special correction for the Oculus Headset
        headBodyOffest = transform.position - headConstraint.position;
    }

    // Update is called once per frame
    void LateUpdate()
    {

        float headRotation = 0;

        if (Input.GetMouseButtonDown(2)) //eliminate if move oculus to mocap all if lines
```

...\MASTER TUDELFT\Graduation\Unity\AL_MoCap_Oculus_setup\Assets\Scripts\RobotRig.cs 2

```
        {
            //The headRotation offset needs to be recorded once when middle mouse is clicked to solve the aligment problem (another script) and then every frame it will be added.
            //Note that in MoCapForAll the axis x correspond to the Oculus' axis y
            headRotation = Camera.transform.rotation.eulerAngles.y - Head.transform.rotation.eulerAngles.x;
            //Debug.Log(headRotation.ToString("F4"));

         }
         else
         {
             headRotation = 0;
         head.Map(Offset, headRotation, Camera);
         hips.Map(Offset, headRotation, Camera);
         ribs.Map(Offset, headRotation, Camera);
         neck.Map(Offset, headRotation, Camera);
         rightUpperArm.Map(Offset,headRotation, Camera);
         rightForeArm.Map(Offset, headRotation, Camera);
         rightHand.Map(Offset, headRotation, Camera);
         leftUpperArm.Map(Offset, headRotation, Camera);
         leftForeArm.Map(Offset, headRotation, Camera);
         leftHand.Map(Offset, headRotation, Camera);
         rightThigh.Map(Offset, headRotation, Camera);
         rightKnee.Map(Offset, headRotation, Camera);
         rightAnkle.Map(Offset, headRotation, Camera);
         leftThigh.Map(Offset, headRotation, Camera);
         leftKnee.Map(Offset, headRotation, Camera);
         leftAnkle.Map(Offset, headRotation, Camera);
         }
     }
 }

```

...UDELFT\Graduation\Unity\AL_MoCap_Oculus_setup\Assets\Scripts\EvaluateBackAngle.cs 1

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using TMPro;

public class EvaluateBackAngle : MonoBehaviour
{
    // Start is called before the first frame update
    [SerializeField] MoCap script;
    public float alphaBack;
    public string popUp;
    Vector3 v;

    void Start()
    {
        alphaBack = 0;
    }

    // Update is called once per frame
    void Update()
    {
        //vector from A (hips) to B(neck)
        v = script.neck.vrTarget.position - script.hips.vrTarget.position;
        // Angle formed by the back vector from A to B with respect to a vector perpendicular to the ground
        alphaBack = Mathf.Acos(v.y / Mathf.Sqrt(Mathf.Pow(v.x, 2) + Mathf.Pow(v.y, 2) + Mathf.Pow(v.z, 2)));
        //Debug.Log(alphaBack.ToString("F4"));

        //Active the popup everytime the back exceeds 0.7
        if (alphaBack > 0.70f)
        {
            PopUpSystem pop = GameObject.FindGameObjectWithTag("GameManager").GetComponent<PopUpSystem>();
            pop.PopUp(popUp);
            Debug.Log("Alpha back > 70");
        }
    }
}

```

```
using System;
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;

//reference https://www.youtube.com/watch?v=4I0vonyqMi8
public class GameManager : MonoBehaviour
{
    public static GameManager Instance;
    public GameObject ExperimentSelector;
    public GameState State;
    public static event Action<GameState> OnGameStateChanged;
    private EvaluateBackAngle scriptEBA;
    private ScoringSystem ScoreScript;
    private ExperimentSelector scriptES;
    public GameObject AirSquatBentArm;

    // Start is called before the first frame update
    void Awake()
    {
        Instance = this;
    }

    private void Start()
    {
        //Get components
        scriptEBA = Instance.GetComponent<EvaluateBackAngle>();
        ScoreScript = Instance.GetComponent<ScoringSystem>();
        scriptES = ExperimentSelector.GetComponent<ExperimentSelector>();

        //Innitalizate. Start State selection
        UpdateGameState(GameState.Start);

    }
    // Update is called once per frame
    public void UpdateGameState(GameState newState)
    {
        State = newState;
        //Jump from one Gamestate to another one. Triggers are included in other scripts
        switch (newState)
        {
            case GameState.Start:
                stateStart(scriptEBA, ScoreScript);
                break;
            case GameState.PlayMode:
                statePlay(scriptEBA, ScoreScript);
                break;
            case GameState.Stats:
                stateStats(scriptEBA);
                break;
            case GameState.Pause:
                statePause(scriptEBA);
                break;
            case GameState.Victory:
                stateVictory(scriptEBA, ScoreScript);
                break;
            default:
                throw new ArgumentOutOfRangeException(nameof(newState),newState, null);
        }
        OnGameStateChanged?.Invoke(newState);
    }
    private void stateStart(EvaluateBackAngle scriptEBA, ScoringSystem ScoreScript)
    {
        //User completes the game and turn of the back angle evaluation feature
        scriptEBA.enabled = false;
        ScoreScript.repetitions = 0;
        ScoreScript.counterUpHigh = 0;
        ScoreScript.counterUpLow = 0;
        ScoreScript.counterUpPerfect = 0;
        ScoreScript.counterLowHigh = 0;
        ScoreScript.counterLowLow = 0;
```

```
        ScoreScript.counterLowPerfect = 0;
        AirSquatBentArm.SetActive(true);


    }
    private void statePlay(EvaluateBackAngle scriptEBA, ScoringSystem ScoreScript)
    {
        //Activates Evaluate Game Angle During the Game
        scriptEBA.enabled = true;
        ScoreScript.enabled = true;
        AirSquatBentArm.SetActive(false);



    }
    private void stateVictory(EvaluateBackAngle scriptEBA, ScoringSystem ScoreScript)
    {
        //User completes the game and turn off the back angle evaluation feature
        scriptEBA.enabled = false;
        ScoreScript.enabled = false;
        //When user press the Experiment bottons restart experience
        PopUpSystem Pop = GameObject.FindGameObjectWithTag("GameManager").GetComponent<PopUpSystem>();
        Pop.PopUp("Victory! You have completed the game. Close the pop up and pick a new game.");

    }

    private void stateStats(EvaluateBackAngle scriptEBA)
    {
        //Statistics on and turn off the back angle evaluation feature
        scriptEBA.enabled = false;
        ScoreScript.enabled = false;
        //Another button to resume the experience IF BUTTON PRESS GET BACK TO PLAY MODE
        PopUpSystem Pop = GameObject.FindGameObjectWithTag("GameManager").GetComponent<PopUpSystem>();
        string NotifyerText = "Personal statistics: \nTop Range. Low=" + ScoreScript.counterUpLow + "/" + ScoreScript.repetitions + " Perfect="+ ScoreScript.counterUpPerfect +"/"+ ScoreScript.repetitions + " High=" + ScoreScript.counterUpHigh + "/" + ScoreScript.repetitions
            + "\nLow Range. Low=" + ScoreScript.counterLowLow + "/" + ScoreScript.repetitions + " Perfect=" + ScoreScript.counterLowPerfect + "/" + ScoreScript.repetitions + " High=" + ScoreScript.counterLowHigh + "/" + ScoreScript.repetitions;
        Pop.PopUp(NotifyerText);

    }
    private void statePause(EvaluateBackAngle scriptEBA)
    {
        //Pause, and turn off the back angle assessment and stop scoring system
        scriptEBA.enabled = false;
        ScoreScript.enabled = false;
        AirSquatBentArm.SetActive(true);

    }
}



public enum GameState
{
    Start,
    PlayMode,
    Stats,
    Pause,
    Victory,
}
```

```
using System;
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;


// This scripts define score obtained in the game.
// The score depends on the vertical displacement
// The vertical displacement range is adapted to each of the user considering their eyes' height.
public class ScoringSystem : MonoBehaviour
{
    public GameObject head;
    public GameObject rightFoot;
    public GameObject ScoreText;
    public static int scoreValue;
    public GameObject box;
    public GameObject topCanvas;
    public GameObject lowCanvas;
    public GameObject ArrowUp;
    public GameObject ArrowDown;
    public GameObject TempScorePrefab;
    private Text ScoreT;
    public bool GoDown;
    public float minUpHeight;
    public float maxLowHeight;
    public int tempScoreValue;
    public float currentHeight;
    public float previousHeight;
    public int repetitions;
    public bool changeActive;
    public int counterUpHigh;
    public int counterUpLow;
    public int counterUpPerfect;
    public int counterLowHigh;
    public int counterLowLow;
    public int counterLowPerfect;
    public GameObject ExperimentSelector;
    private ExperimentSelector scriptES;
    public bool tooHigh;
    public bool tooLow;

    // Start is called before the first frame update
    void Start()
    {
        scriptES = ExperimentSelector.GetComponent<ExperimentSelector>();
        ScoreT = ScoreText.GetComponent<Text>();
        scoreValue = 0;
        minUpHeight = 0;
        maxLowHeight = 0;
        tempScoreValue = 0;
        repetitions = 0;
        changeActive = false;
        GoDown = true;
        counterUpHigh=0;
        counterUpLow=0;
        tooHigh = false;
        tooLow = false;
        StartCoroutine(PreviousHeight());
    }

    IEnumerator PreviousHeight()
    {
        while (true)
        {
            previousHeight = box.transform.position.y;
            //Debug.Log("runningCoroutinePreviousHeight");
            yield return new WaitForSeconds(0.15f);

        }
    }

```

```
    // Update is called once per frame
    void Update()
    {
        //When the middle button of the mouse is pressed the calibration of the game to user's eyes' height is performed by defining the lifting heights.
        if (Input.GetMouseButtonDown(2))
        {
            float reference = head.transform.position.y - rightFoot.transform.position.y;
            Debug.Log("Calibration completed");
            minUpHeight = reference * 0.55f;
            topCanvas.transform.position = new Vector3(topCanvas.transform.position.x,minUpHeight +0.15f, topCanvas.transform.position.z);
            maxLowHeight = reference*0.3f;
            lowCanvas.transform.position = new Vector3(lowCanvas.transform.position.x, maxLowHeight -0.15f, lowCanvas.transform.position.z);
        }

        currentHeight = box.transform.position.y;

        //When trigger GoDown == true the user needs to go down. Set feedback on and off
        if (GoDown == true && minUpHeight!=0)
        {
            DecideScoreDown(tempScoreValue, maxLowHeight, box, changeActive, tooLow);
            ArrowDown.SetActive(true);
            ArrowUp.SetActive(false);
            if (scriptES.SelectedExperiment == 0)
            {
                lowCanvas.SetActive(true);
                topCanvas.SetActive(false);
            }
            else
            {
                lowCanvas.SetActive(false);
                topCanvas.SetActive(false);
            }
        }
        //When trigger GoDown == false the user needs to go up. Set feedback on and off
        else if (GoDown == false && minUpHeight != 0)
        {
            DecideScoreUp(tempScoreValue, minUpHeight, box, changeActive, tooHigh);
            ArrowDown.SetActive(false);
            ArrowUp.SetActive(true);
            if (scriptES.SelectedExperiment == 0)
            {
                topCanvas.SetActive(true);
                lowCanvas.SetActive(false);
            }
            else
            {
                lowCanvas.SetActive(false);
                topCanvas.SetActive(false);
            }
        }
        // Special case for Experiment 2 (Statistics)
        if (repetitions == 5 && scriptES.StatsOn == true)
        {
            GameManager.Instance.UpdateGameState(GameState.Stats);
        }
        // When 10 squats are completed GameState changes to Victory
        else if (repetitions >= 10)
        {
            GameManager.Instance.UpdateGameState(GameState.Victory);
            topCanvas.SetActive(false);
            lowCanvas.SetActive(false);
        }
    }


    public void DecideScoreUp(int tempScoreValue, float minUpHeight, GameObject box, bool changeActive, bool tooHigh)
    {
        float centreUpHeight = minUpHeight + 0.15f;
```

```
        float maxUpHeight = minUpHeight + 0.3f;

        if (box.transform.position.y > minUpHeight && box.transform.position.y < maxUpHeight && tooHigh == false)
        {
            //Temporary Score records the instant score per motion
            tempScoreValue = Mathf.RoundToInt(100 - 80 * (Mathf.Abs(box.transform.position.y - centreUpHeight))/(centreUpHeight - minUpHeight));
            changeActive = true;
            Debug.Log("MinUpHeightReached");
            tooHigh = false;
        }

        if (box.transform.position.y > maxUpHeight)
        {
            changeActive = true;
            tempScoreValue = 0;
            Debug.Log("Too high");
            tooHigh = true;
            if (scriptES.SelectedExperiment == 2)
            {
                //For the Experiment 3 (Pop Ups) when the user lifts the water jug excesively a pop up message appears
                PopUpSystem Pop = GameObject.FindGameObjectWithTag("GameManager").GetComponent<PopUpSystem>();
                string PopUpHeightBox = "Game Paused, try not to lift the box so high";
                Pop.PopUp(PopUpHeightBox);
                GameManager.Instance.UpdateGameState(GameState.Pause);
            }
        }

        if (currentHeight < previousHeight && changeActive==true)
        {

            //We can activate goDown as soon as it stop going up within the lifting range
            GoDown = true;
            changeActive = false;
            var go = Instantiate(TempScorePrefab, new Vector3(0, 0.75f, 1), Quaternion.identity);
            go.GetComponent<TextMesh>().text = tempScoreValue.ToString();
            ScoreT.text = "" + tempScoreValue;
            //The last Temporary Score recorded while going upwards is added to the total score
            scoreValue += tempScoreValue;

        if (tooHigh == true )
        {
            counterUpHigh += 1;
        }
        else if ( tooHigh == false && tempScoreValue <40)
        {
            counterUpLow += 1;
        }
        else if ( tooHigh == false && tempScoreValue >=40)
        {
            counterUpPerfect += 1;
        }

            tempScoreValue = 0;
            repetitions += 1;

        }
        ScoreT.text = "Score=" + scoreValue + "/2000";
    }


    public void DecideScoreDown(int tempScoreValue, float maxLowHeight, GameObject box, bool changeActive, bool tooLow)
    {
        float centreDownHeight = maxLowHeight - 0.15f;
        float minLowHeight = maxLowHeight - 0.3f;

        if (box.transform.position.y < maxLowHeight && box.transform.position.y > minLowHeight && tooLow == false)
        {
            tempScoreValue = Mathf.RoundToInt(100 - 80 * (Mathf.Abs(box.transform.position.y - centreDownHeight)) / (centreDownHeight-minLowHeight));
```

```
            changeActive = true;
            Debug.Log("MaxLowHeightReached");
            tooLow = false;
        }

        if (box.transform.position.y < minLowHeight)
        {
            changeActive = true;
            tempScoreValue = 0;
            Debug.Log("Too low");
            tooLow = true;
            if (scriptES.SelectedExperiment == 2)
            {
                //For the Experiment 3 (Pop Ups) when the user moves the water jug excesively low a pop up message 
                  appears
                PopUpSystem Pop = GameObject.FindGameObjectWithTag("GameManager").GetComponent<PopUpSystem>();
                string PopUpHeightBox = "Game Paused, try not to move the box so low";
                Pop.PopUp(PopUpHeightBox);
                GameManager.Instance.UpdateGameState(GameState.Pause);
            }
        }

        if (currentHeight > previousHeight && changeActive == true)
        {
            //We can deactivate goDown as soon as it stop going down within the squating range
            GoDown = false;
            changeActive = false;
            var go = Instantiate(TempScorePrefab, new Vector3(0, 0.75f, 1), Quaternion.identity);
            go.GetComponent<TextMesh>().text = tempScoreValue.ToString();
            ScoreT.text = "" + tempScoreValue;
            scoreValue += tempScoreValue;

            if (tooLow == true)
            {
                counterLowLow += 1;
            }
            else if (tooLow == false && tempScoreValue < 40)
            {
                counterLowHigh += 1;
            }
            else if (tooLow == false && tempScoreValue >= 40)
            {
                counterLowPerfect += 1;
            }

            tempScoreValue = 0;
        }
        ScoreT.text = "Score=" + scoreValue;
    }
}
```

```
using System;
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using System.IO;
using System.Linq;
using System.Text;
using System.Threading.Tasks;

public class CSVWrite : MonoBehaviour
{
    string filename = "";
    private EvaluateBackAngle scriptEBA;
    private ScoringSystem ScoreScript;
    public GameObject GameManager;
    public GameObject box;

    [System.Serializable]
    // Start is called before the first frame update
    public class UserData
    {
        public float backAngle;
        public float height;
    }

    public UserData myUserData;
    void Start()
    {
        scriptEBA = GameManager.GetComponent<EvaluateBackAngle>();
        ScoreScript = GameManager.GetComponent<ScoringSystem>();

        //Definition of the CSV file
        filename = Application.dataPath + "/test_"+ DateTime.Now.Year + DateTime.Now.Month + DateTime.Now.Day + "_"+ DateTime.Now.Hour + DateTime.Now.Minute + DateTime.Now.Second + ".csv";
        TextWriter tw = new StreamWriter(filename, false);
        tw.WriteLine("Time. Back Angle. Height");
        tw.Close();
        StartCoroutine(WriteCSV());
    }

    // Update is called once per frame

    IEnumerator WriteCSV()
    {
        while (true)
        {
            //Content to be written in the CSV file
            myUserData.backAngle = scriptEBA.alphaBack;
            myUserData.height = box.transform.position.y;
            try
            {
                using (System.IO.StreamWriter file = new System.IO.StreamWriter(@filename, true))
                {
                    //Witting action (Dots are used as delimeters since the floats' decimals are given with comas
                    file.WriteLine((DateTime.Now.ToLongTimeString() + ":" + DateTime.Now.Millisecond + "." + myUserData.backAngle.ToString("F2") + "." + myUserData.height.ToString("F2")));
                }
            }
            catch (Exception ex)
            {
                throw new ApplicationException("This program did not work", ex);
            }
            //Set a delay depending on the desired records per second
            yield return new WaitForSeconds(0.20f);
        }
    }
}
```

...UDELFT\Graduation\Unity\AL_MoCap_Oculus_setup\Assets\Scripts\TransformPosition.cs 1

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;

//Script used to change the system of refence from the Oculus' to the MoCapForAll's one.
//Both hands and head are adjusted.

public class TransformPosition : MonoBehaviour
    {
    private Vector3 MoCapPosition;
    public GameObject Camera;
    public GameObject Head;
    public GameObject ControllerL;
    public GameObject ControllerR;
    public GameObject CameraRig;
    public Vector3 Offset;

        // Update is called once per frame
        void Update()
        {
            float headRotation = 0;
            if (Input.GetMouseButtonDown(2))
            {
                MoCapPosition = Head.transform.position - Camera.transform.position; //store the position in a public variable
                MoCapPosition+= Offset;
                transform.position = MoCapPosition; //update the position
                Debug.Log("VR headset position updated");
                //As offset the rotation needs to be recorded once when click and then every frame it will be added.
                headRotation = Camera.transform.rotation.eulerAngles.y - Head.transform.rotation.eulerAngles.x;
                Debug.Log(headRotation.ToString("F4"));
                CameraRig.transform.RotateAround(Camera.transform.position, new Vector3(0, -1, 0), headRotation);
        }

        }
    }
```

...\Graduation\Unity\AL_MoCap_Oculus_setup\Assets\Scripts\SharedMemoryToTransform.cs 1

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

public class SharedMemoryToTransform : SharedMemoryReader
{
    // output from shared memory
    public Transform[] data;

    // set as Transform
    public override void OutputData(float[] buffer)
    {
        for (int i = 0; i < data.Length && i * 7 + 6 < buffer.Length; i++)
        {
            int offset = i * 7;
            data[i].rotation = new Quaternion(buffer[offset], buffer[offset + 2], -buffer[offset + 1], buffer[offset + 3]); // (UE4.rot.x, -UE4.rot.z, UE4.rot.y, UE4.rot.w)
            data[i].position = new Vector3(buffer[offset + 4], buffer[offset + 6], -buffer[offset + 5]) / 100.0f; // (UE4.pos.x, -UE4.pos.z, UE4.pos.y) / 100

        }
    }
}
```

Feedback impact on the performance

You are being invited to participate in a research study titled "Feedback impact on game's performance". This study is being conducted by Alejandro Lazaro from the TU Delft, supervised by Jered Vroon and Erik Tempelman and for the company Ethereal Matter.

The purpose of this research study is to assess how different feedback alternatives affect the performance on VR games, and will take you approximately 20 to 40 minutes to complete. The research consist in 3 different experiments, each of which is followed by a questionnaire. The data will be used for further develop a platform that combines VR and force feedback enabling intense workouts, named the Ethereal Engine.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. Positional data will be recorded during the experiment. All the data obtained from the experiment is completely anonimous and will be used exclusively for research purposes.

Please abstain from taking part in this experiment if you ever suffer an epilepsy episode.

During the questionnaire you will be asked to give the formulier back to the researcher to select the order in which you performed the experiments.

By clicking "Next" button you agree the terms and conditions stated previously in this text

*Obligatorio

Experiment Selection

Give the questionnaire back to the researcher

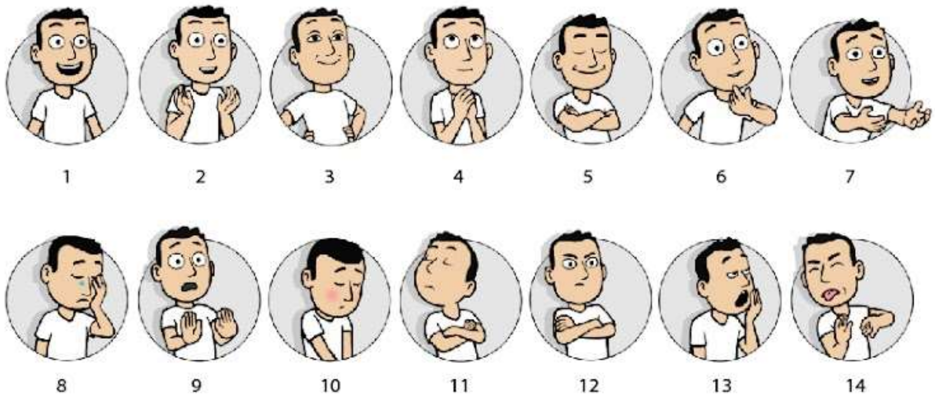
1. Select the Experiment *

Marca solo un óvalo.

- ⬭ Experiment A *Salta a la pregunta 2*
- ⬭ Experiment B *Salta a la pregunta 12*
- ⬭ Experiment C *Salta a la pregunta 22*
- ⬭ Experiment Comparison *Salta a la pregunta 33*

Experiment A

2. Which of the following illustrations reflects best how you felt during the experiment?



Marca solo un óvalo.

- Option 1
- Option 2
- Option 3
- Option 4
- Option 5
- Option 6
- Option 7
- Option 8
- Option 9
- Option 10
- Option 11
- Option 12
- Option 13
- Option 14

3. How would you describe the emotion you chose in one word?

4. What triggered that emotion?

____
____
____
____
____

To which extent do you agree with each of the following statements:

5. I did understand the feedback provided during the experiment.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

6. The feedback was useful to understand how to get a better score in the game.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

7. The feedback I received positively influenced my performance in the game.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

8. The feedback helped me easily understand how to complete the exercises while keeping a correct posture.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

9. The feedback does positively affect the engagement of the experience.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

10. During the experiment, I felt confused by the feedback I received.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

11. During the experiment, I felt criticized by the feedback

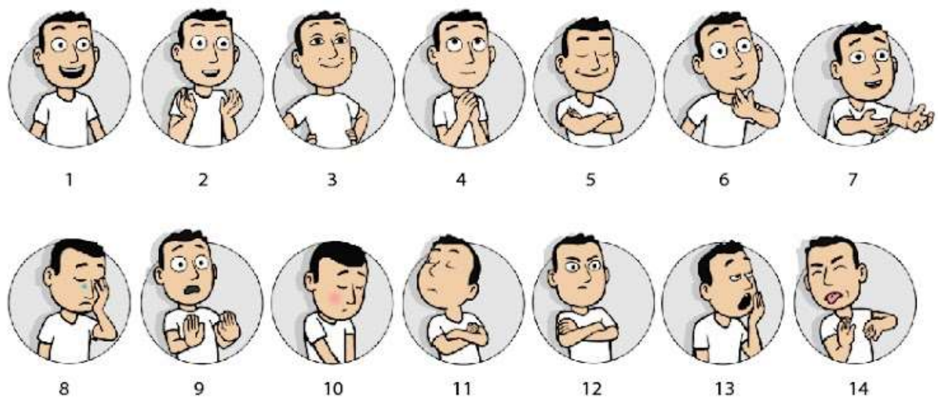
Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

Salta a la pregunta 1Salta a la pregunta 1

Experiment B

12. Which of the following illustrations reflects best how you felt during the experiment?



Marca solo un óvalo.

- Option 1
- Option 2
- Option 3
- Option 4
- Option 5
- Option 6
- Option 7
- Option 8
- Option 9
- Option 10
- Option 11
- Option 12
- Option 13
- Option 14

13. How would you describe the emotion you chose in one word?

14. What triggered that emotion?

To which extent do you agree with each of the following statements:

15. I did understand the feedback provided during the experiment.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

16. The feedback was useful to understand how to get a better score in the game.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

17. The feedback I received positively influenced my performance in the game.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

18. The feedback helped me easily understand how to complete the exercises while keeping a correct posture.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

19. The feedback does positively affect the engagement of the experience.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

20. Reducing the feedback during the game helps me keep focused on my body posture during the game.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

21. During the experiment, I felt criticized by the feedback.

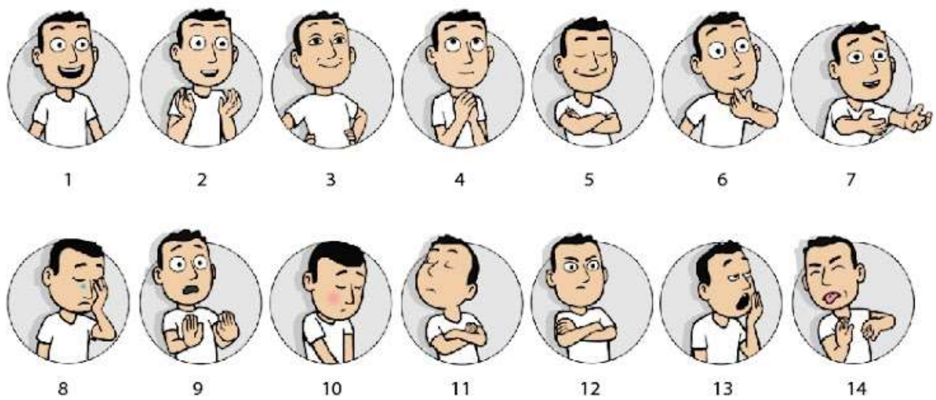
Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

Salta a la pregunta 1Salta a la pregunta 1

Experiment C

22. Which of the following illustrations reflects best how you felt during the experiment?



Marca solo un óvalo.

- Option 1
- Option 2
- Option 3
- Option 4
- Option 5
- Option 6
- Option 7
- Option 8
- Option 9
- Option 10
- Option 11
- Option 12
- Option 13
- Option 14

23. How would you describe the emotion you chose in one word?

____

24. What triggered that emotion? *

To which extent do you agree with each of the following statements:

25. I did understand the feedback provided during the experiment.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

26. The feedback was useful to understand how to get a better score in the game.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

27. The feedback I received positively influenced my performance in the game.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

28. The feedback helped me easily understand how to complete the exercises while keeping a correct posture.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

29. The feedback does positively affect the engagement of the experience.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

30. During the experiment, I felt confused by the feedback I received.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

31. During the experiment, I felt criticized by the feedback.

Marca solo un óvalo.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

32. How frequently did you see a pop-up message during the experiment? (Write a number)

____

Salta a la pregunta 1Salta a la pregunta 1

Experiment Comparison

33. From the 3 experiments described which one do you consider BEST in terms of the following parameters:

Marca solo un óvalo por fila.

	Experiment A (Live visual effects)	Experiment B (Statistics)	Experiment (Pop-Up)
Understandability	◯	◯	◯
Satisfaction/engagement	◯	◯	◯
Inspiration	◯	◯	◯
Effectiveness	◯	◯	◯
Safety	◯	◯	◯

34. From the 3 experiments described which one do you consider WORST in terms of the following parameters:

Marca solo un óvalo por fila.

	Experiment A (Live visual effects)	Experiment B (Statistics)	Experiment (Pop-Up)
Understandability	◯	◯	◯
Satisfaction/engagement	◯	◯	◯
Inspiration	◯	◯	◯
Effectiveness	◯	◯	◯
Safety	◯	◯	◯

Demographics

38. What do you do in the gym?

Selecciona todos los que correspondan.

- [ ] Cardio
- [ ] Lifting weight
- [ ] Gym classes (Zumba, Yoga, Pilates, Crossfit, Boxing)
- [ ] Follow personal trainer advice
- [ ] Otro: ______________________

39. What are your motivations for going to the gym?

Selecciona todos los que correspondan.

- [ ] Stay healthy
- [ ] Build up muscles
- [ ] Physical rehabilitation
- [ ] Enjoy and have fun/compete with my friends
- [ ] Otro: ______________________

Demographics

40. How often do you play video games?

Marca solo un óvalo.

- ( ) Never *Salta a la pregunta 43*
- ( ) 1-3 times a month
- ( ) 1-3 days a week
- ( ) More than 3 days a week

Demographics

41. What kind of video games do you play?

Selecciona todos los que correspondan.

- [ ] Active gaming (Nintendo Switch, Wii, VR sets)
- [ ] Stationary gaming (PS4, Xbox, Computer games)
- [ ] Solo games
- [ ] Multiplayer

42. What is your motivation for gaming?

Selecciona todos los que correspondan.

- [ ] Escaping the real world
- [ ] Relaxation
- [ ] Having fun
- [ ] Meeting friends

Demographics

43. How familiar are you with VR?

Marca solo un óvalo.

- ( ) I have never experienced it
- ( ) I have ocasionally experienced it
- ( ) I am a regular user
- ( ) I am a developer

Thanks for participating!

Thank you for taking the time out of your busy schedules to participate in this study.

44. As a last request, do you give permission to anonymously quote your responses in research outputs *

Marca solo un óvalo.

- ( ) Yes
- ( ) No

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