SCHOOL OF COMPUTATION,
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INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Bachelor's Thesis in Informatics: Games Engineering

Virtual Reality Application about Historical Fencing

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Virtual Reality Anwendung zu Historischem Schwertkampf

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I confirm that this bachelor's thesis is my own work and I have documented all sources and material used.

Munich, 24.09.2024 Jonas Hack

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Abstract

Fencing is often depicted in video games with a medieval setting. Due to the limitations of their interaction methods and commercial concerns, they are typically unable or unwilling to fully capture the historical realities. First hand knowledge on the topic is difficult to acquire, as the training of historical fencing as sport (HEMA) is inaccessible to many. This paper investigates the viability of Virtual Reality to serve as a training and educational tool on the topic of historical fencing.

For this purpose a proof-of-concept application with a corresponding tangible is created. The tangible is designed to mimic a 15th century longsword, taking its dynamic properties into account. The application consists of three exercises depicting fundamental fencing techniques. The success of this prototype is evaluated by means of a user-study, including a small pool of subject matter experts.

Evaluation of the data supports the usage of VR. The application's average SUS-Score is 81.15. The desired teaching effect is achieved, with users' average performance scores improving by over 97%. The added value is demonstrated by means of A/B testing, with an average score improvement of 16%, though comparative data regarding the user ratings is inconclusive. The subject matter expert interviews are overall positive, with a noted advantage over traditional training of edge alignment.

This demonstrates the viability of VR for the training and teaching of historical fencing. Further research is required to tackle some of the challenges arising from the unique requirements of armed combat sports.

Index Terms - VR, Tangible, Weapon Dynamics, Historicity, Historical Fencing, HEMA

Contents

1. Introduction

1.1. Motivation

Swordsmanship has fascinated many people for a long time. Typically most depictions fail to capture the reality of historical fencing. Video games in particular often fail to do so, possibly due to inadequate interaction methods, such as gamepads. For many it is also not possible to acquire first-hand experience in historical fencing through the practice of it as a sport, as few dedicated historical fencing clubs exist and equipment is rather expensive. Virtual reality is being employed as a training method in many fields. It may lower the bar of entry in this one as well. This paper investigates the viability of virtual reality as a training and educational tool for historical fencing.

1.2. Terms and Definitions

1.2.1. Historical Fencing

This paper focuses on late medieval fencing using the longsword, as reconstructed by the Historical European Martial Arts (HEMA) community. HEMA is a term covering multiple martial arts, which have been reconstructed from surviving primary sources, mostly dating to the European Middle Ages. [Kel19]

1.2.2. Virtual Reality

Virtual Reality (VR) is a term used for real-time applications presenting a fully virtual environment to the user as if it were their real surroundings, achieving a sense of immersion and spatial presence. Typically, a Head Mounted Display (HMD), also known as a VR headset, is used.

1.2.3. Tangible

A Tangible User Interface, or tangible, is a category of interaction methods relying on physical interaction with the virtual world [Hor15], such as steering wheel controllers. In the context of this paper it specifically describes interactive devices representing diegetic objects in the virtual world.

2. Related Work

2.1. Commercial

2.1.1. Non-VR Games

Many commercially available video games, taking place in the Middle Ages or medieval inspired fantasy, depict some sort of swordsmanship. Most do not attempt to accurately portray historical fencing. Those that do typically have to compromise on the historicity in order to facilitate engaging gameplay.

Kingdom Come: Deliverance

Kingdom Come: Deliverance is a role-playing game set in early 15th century Bohemia [War18]. It has been hailed as the game with the most historically accurate swordsmanship. As demonstrated in an earlier paper, the game's depiction is overall very historically accurate, but simplifies the subject matter in some aspects [Hac]. While the visual representation of the fencing techniques is detailed, the corresponding gameplay mechanics lack some critical aspects, such as the concept of *Fühlen* (which is explained in Chapter 3). This is likely due to limitations on the achievable complexity using standard input methods.

Hellish Quart

Hellish Quart is a fighting-game set in 17th century eastern Europe [Kub21]. "The game is a love letter to [...] HEMA" [Kub22, 0:30], even including a mode to simulate HEMA sparring. The game's input control scheme makes some concepts of historical fencing explicit. There is for example a button dedicated to binding blades and one to switch stances [Kub22]. This results in a more in-depth combat system, presenting HEMA fairly accurately. It does however, still not allow full control over the sword, leading to the same issue of hiding concepts of historical swordsmanship behind a layer of abstraction. The game's physical simulation of the blades is a noteworthy advancement, which may be useful to academic approaches as well.

Figure 2.1.: Duel in *Kingdom Come: Deliverance* [War18]

Figure 2.2.: Duel in *Hellish Quart* [Kub21]

Half Sword

Half Sword is a physics-based combat game set in the 15th century [Gam23]. Its main distinguishing feature is the full control over the character's sword, using a computer mouse. This leads to emerging gameplay concepts, which closely match those of historical fencing. This input scheme, while allowing for a more direct translation of input to action, is still inadequate to fully control a sword in all six degrees of freedom.

Figure 2.3.: Duel in *Half Sword* [Gam23]

2.1.2. VR Games

There are also a number of VR games depicting swordsmanship. The controllers, which are fully tracked in three-dimensional space, allow for the intuitive and diegetic wielding of swords. Nevertheless, there are a number of unsolved issues. Pitura summarizes the current state of these games in their master's thesis [Pit23]. While their analysis does not consider historicity, it does provide a comprehensive overview of the features necessary for a good digital representation of swordsmanship. Their factors are as follows (paraphrased) [Pit23]:

- Consideration of weapon weight
- Physically simulated parries
- *Bindung* and *Fühlen* (see Chapter 3)
- Distinction between blade edge and flat
- Edge alignment
- Distinction of the point of the sword
- Flexing blades
- 3D tracking
- Real life locomotion
- Environment interaction
- Accuracy of depicted fencing

Using these factors to analyze multiple of the most widely known VR games, they conclude that the games are not accurate representations of fencing. During this analysis, they also present some possible methods of improving VR fencing games.

2.2. Academic

2.2.1. Martial Arts in VR

VR Training module for Maithari of the Indian Marial Art Kalari

Singh et al. present their approach to the development of a VR training module for preliminary exercises for the Indian martial art *Kalari* [SDK21]. These exercises consist of various body poses and calisthenics. This chosen exercise format provides a simple foundation to build on for the exercises implemented in our paper. For the implementation they describe in great detail the fundamentals of how to create, animate and import characters into the Unity game engine. They also propose the creation of a technique evaluation system, but do not elaborate on its intended functionality or utilized method of technique analysis.

Evaluation of VR Training to Improve Karate Performance

Witte et al. performed a long term study evaluating VR as a method for martial arts (*Karate*) training by comparing the trainees' performance to a control group, which trained using traditional methods [al22]. Their exercises consist of a virtual opponent performing (motion captured) attacks to which the user has to respond. They then tested the users under real world conditions and concluded that VR improved the user's response time. They could however, not prove that these effects translated to real world conditions, though the tested *Karate* athletes responded positively to the virtual exercises. This research indicates the possibility of successfully using VR to teach martial arts in general, a prerequisite for our paper.

Utilization of Full-Body Tracking & Physically Simulated Opponents

Takala et al. enable the virtual training of *Karate* techniques using the lower body, such as kicks, by integrating a full-body tracking system into their application [al20b]. Additionally, they rely on fully physically simulated opponents to create a true-to-life simulation of the martial art. They also improve on traditional training methods by including additional modes in their application, such as a rhythm game and performance playback. These approaches are likely to apply to historical fencing as well.

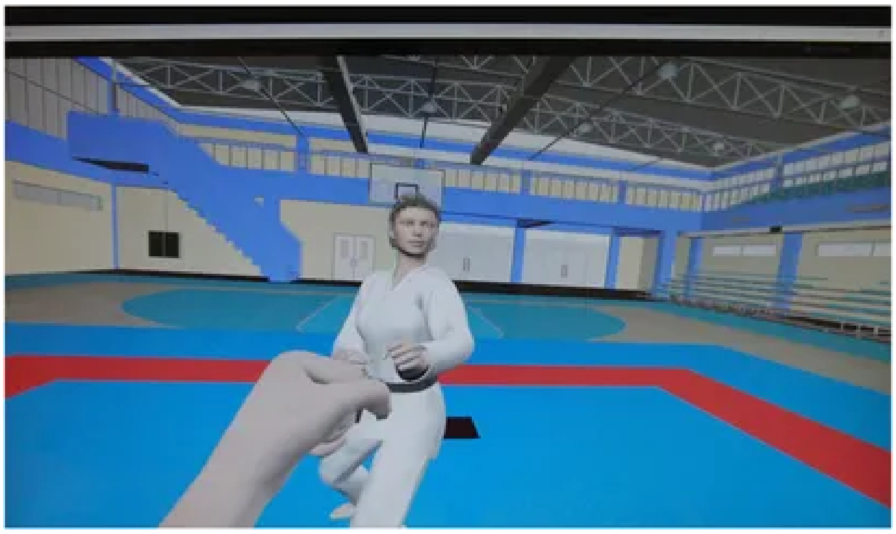


Figure 2.4.: Karate Training in VR as implemented by Witte et al. [al22]

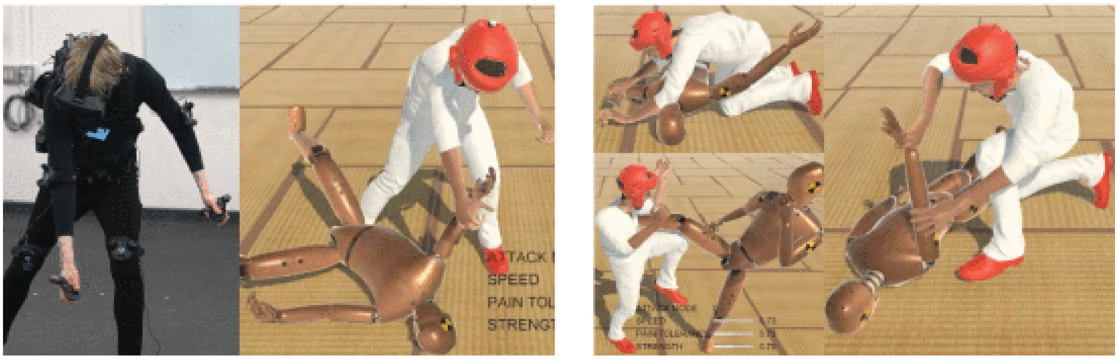


Figure 2.5.: Karate Training in VR as implemented by Takala et al. [al20b]

HEMA Technique Evaluation

There are two noteworthy papers about the evaluation of performed HEMA techniques. Both rely on full-body motion captured data of fencers. They do however rely on different algorithms to determine the user's performance. Grontman et al. analyze the euclidean distance of each tracker to the optimal position, while adjusting for speed differences using dynamic time warping [al20a]. Klempous et al. on the other hand makes use of neural networks, combining multiple classifiers for a more accurate result [al21]. This approach has some real-time capability, making it suitable for interactive feedback in a VR application, such as the one developed as part of our paper.

2.2.2. Physics of Swords

Swords can be analyzed in respects to their physical properties. This allows accurate, quantitative comparisons between different swords, as well as the prediction and evaluation of their performance in practice. The research by Turner [Tur02] and Chevalier [Che14] [Che19][Vin], as well as the extensive course by Föll [Fölnd] analyze and theorize about these properties in depth. Much of this analysis, such as the metallurgical background, is not relevant for the scope of this paper. The physical properties determining the handling, known as *Weapon Dynamics*, are critical in the creation of a convincing sword replica tangible.

The main physical properties to consider are [Fölnd][Tur02][Che19]:

- Total Mass m
- Center of Mass COM, aka. the point of balance
- Moment of Inertia I
- Radius of Gyration k

Other aspects beyond the scope of this paper are covered in-depth in these works. Föll uses swords as a means to teach topics ranging from metallurgy to rigid-body physics, citing both Chevalier and Turner [Fölnd]. Chevalier's articles cover multiple topics, but focus mainly on the measurement of swords [Che19], culminating in a sword property calculator [Vin]. Turner covers similar topics, but also includes a particularly useful section on the creation of a feel simulator [Tur02, p.16]. His work is what this paper's tangible is based on, which is why it is explained in more depth in Chapter 5.

3. Historical Background

To create an application about historical fencing, one must first analyze the historical background and the modern attempts at reconstructing it as a combat sport. Such an analysis has recently been conducted in one of our previous papers. This chapter is largely identical to this previous paper [Hac].

3.1. Sources

Some medieval master swordsmen chose to document their martial arts, sometimes as comprehensive manuals. These manuals are called *Fechtbücher* [Sch13]. These fencing manuals often reference the teachings of Johannes Liechtenauer, a fencing master from the 14th century who can be considered the founding father of the German tradition of historical fencing, reaching to Joachim Meyer in the 16th century [Aba08, p.11].

Wolfang Abart was among the first to create a modern comprehensive practical manual based on his own interpretations of the *Fechtbücher* [Sch13]. Herbert Schmidt followed suit in 2008. Their books are based on both the medieval primary sources and their own practical experience. As of now the formerly lost martial art of historical European fencing is fairly well documented [Sch13]. Most of this available data is on the longsword. Consequently, this paper focuses on it as well.

On the basis of the transcriptions and interpretations the combat sport HEMA formed in the late 1990s [Kel19, p.120]. HEMA is at its core a sport, and its practitioners are mostly athletes [Kel19, p.121]. Additionally, there are academically viable aspects. Many HEMA athletes still work directly with the primary sources and treat their sport like experimental archaeology [Kel19, p.123].

3.2. Critical Concepts of Swordsmanship

3.2.1. Mensur

Mensur is the distance between the fencers. It is not defined by an exact length, but by discrete, functionally identical ranges. Commonly, one distinguishes between the following four *Mensuren*:

- *Weite Mensur* is any distance too far to engage the opponent. Herbert Schmidt defines it by the necessity of two steps to reach the opponent [Sch15, p.29]. Wolfgang Abart on the other hand defines it as any distance between the fencers before they engage [Aba08, p.93].
- *Mittlere Mensur* is the distance where one step is needed to engage the opponent. Wolfgang Abart additionally specifies that the initial engagement, called *Zufechten* takes place at this distance [Aba08, p.93].
- *Nahe Mensur* is the distance at which either fencer can strike at the other without taking a step [Aba08, p.93][Sch15, p.29].

3.2.2. Vier Blößen

The *Vier Blößen* are the areas one could target on a human body. They are the four quadrants centered around the waist. Each *Blöße* is vulnerable to a group of attacks coming from its respective direction. Both Abart and Schmidt stress the impossibility of defending against attacks to all the *Blößen* at once [Aba08, p.44][Sch15, p.33].

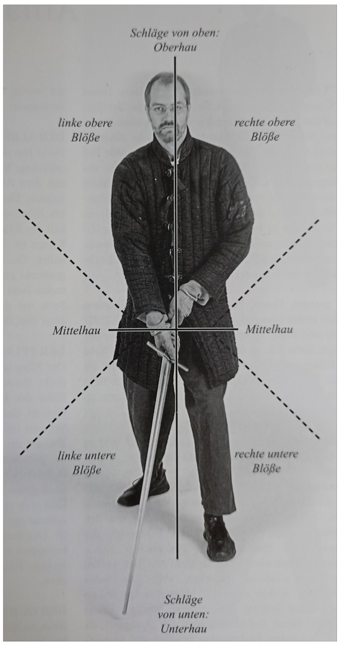


Figure 3.1.: The *Vier Blößen* annotated with attack directions by Schmidt [Sch15, p.33]

3.2.3. Huten

The *Huten* are guards or stances any experienced fencer will naturally assume. They are positions from which a fencer can start, end in or even move through. They are not necessarily poses a fencer should remain in for an extended amount of time [Aba08, p.15]. The *Huten* serve as tactical tools, as each *Hut* covers and threatens only some of the *Blößen* easily. Schmidt even describes fencers switching between *Huten* to gain an advantage before any blows are dealt [Sch15, p.34]. For modern academics the *Huten* serve as precise terms to describe any common action a fencer could take.

3.2.4. Timing

The timing in historical fencing does not describe the speed of an action, but the point in time compared to the action of the opponent. It is a way to describe which fencer is on the offensive or defensive. It also hints at cause and effect. This usually takes the form of compelling the opponent to defend by threatening one of their openings using an attack.

There are three stages: [Aba08, p.97][Sch15, pp. 54-55]

- *Vor* applies to any action taken through one's own initiative, without a prior action by the opponent.
- *Indes* applies to any action taken at the same time as an opponents action.
- *Nach* applies to any action, which merely reacts to an opponents action.

The *Indes* stage is often the transition from defense to offense and thus considered to be used by particularly skillful fencers [Aba08, p.97][Sch15, pp. 54-55].

3.2.5. Meisterhaue

Meisterhaue are strikes, which both attack an opponent's *Blöße*, and at the same time defend ones own Blöße. They can be used as an opening attack during the *Vor* to prevent a possible counterattack. They are predominantly used during *Indes* to defend against a strike and attack at the same time [Aba08, p74][Sch15, p.42].

3.2.6. Bindung

When two swords meet on the edge of their blades, they stick instead of sliding like they would when contacting on the flat sides of the blades. This is called the *Bindung*.

An important concept during the *Bindung* is the so-called *Fühlen*. It is the act of determining the amount and direction of force the opponent puts on their blade [Sch15, p.132]. This information is instrumental in tactical decision making. For example, when an opponent uses a lot of force, it might be prudent to use little force yourself and to deflect their sword to the side. On the other hand, if the opponent uses little force, it might be sensible to push their sword aside forcefully.

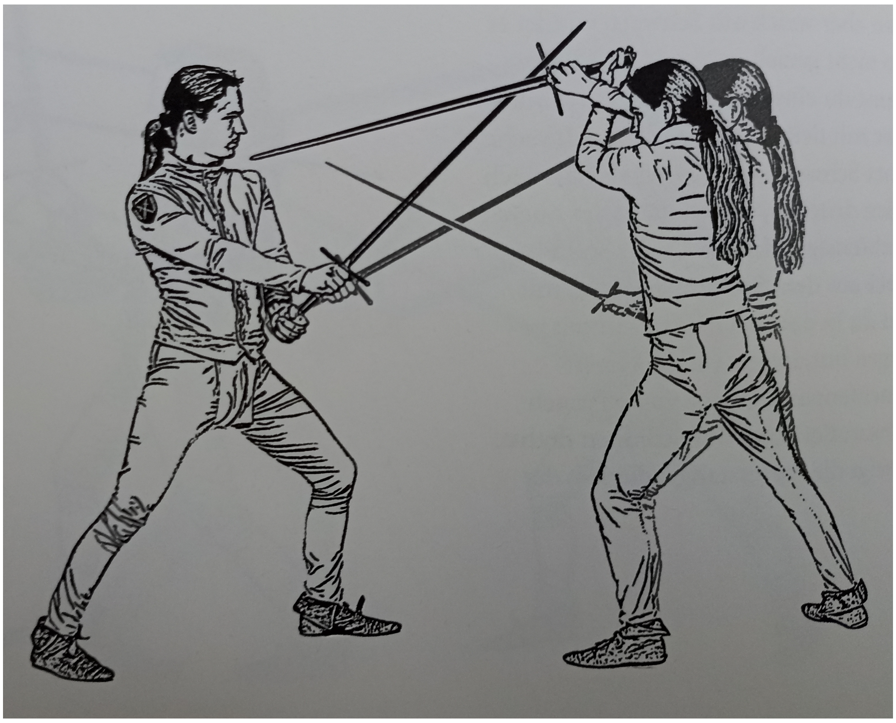


Figure 3.2.: *Winden* as depicted by Abart [Aba08, p.106]

The process moving the sword between low and high to displace the opponent's sword is called *Winden* [Aba08, p.101]. It uses both, the information gained by *Fühlen*, and the advantage of leverage due to the relative length of the swords resulting from the point of contact of the blades. When contact is close to the handle, it is easier to control the opponent's blade than if the contact was made closer to the point of the sword [Aba08, p. 98]. Many advanced techniques such as *Duppliëren* and *Mutieren* further expand on *Winden*.

4. Project Overview

The creation of a full true-to-life VR simulation is outside the scope of this paper. It is a project, which inevitably must undergo multiple iterations. This paper serves as a proof-of-concept, showcasing the potential of VR for the teaching and training of HEMA specifically. Nevertheless, a long-term plan for a possible continuation project, with avenues of improvement and advancement, consisting of clear steps shall be devised.

4.1. Historical Research

The first step of the project must be the compilation of the current state of research regarding historical fencing. An understanding of it, both as a sport and as a living history, is necessary to design and implement exercises, which are useful as training and educational tools. The reconstructive efforts of HEMA practitioners serve as a sufficient source for the purpose of this project. Chapter 3 is an overview of all the important concepts in historical fencing relevant to this paper, though additional research may be necessary for the completion of a possible long-term project.

4.2. Proof of Concept

4.2.1. Preliminary Goals

Before an application depicting the entirety of historical fencing can be created, a smaller proof-of-concept application, consisting of multiple exercises and utilizing a tangible, must validate the suitability of VR as a training and educational tool for HEMA, given its unique challenges. The added value of the utilization of VR needs to be evaluated and the achieved learning effect of users must be quantified. This is the purpose of this paper. Explicitly outside the scope are full-body tracking, fully physical simulation of blade interactions, and digital sparring.

4.2.2. Implementation

The implementation of the proof-of-concept consists of two stages. The first is the construction of a tangible, closely matching historical longswords. The second is the development of a VR application, which consists of multiple exercises depicting historical techniques. Special care must be taken to make use of the advantages of a virtual training environment. This, as well as the practical limitations inherent to a demo-application, influences the choice of exercises.

4.2.3. Evaluation

The evaluation of the implementation shall consist of a user-study, with 15 - 20 participants, at least one of whom is a subject matter expert, such as a long time practitioner of HEMA. Quantitative data is needed to determine the success of the teaching methods. This data is to be gathered by measuring the participant's performance throughout the user-study.

4.3. Long-Term Development

Once the suitability of VR as a training tool for HEMA and educational value regarding historical fencing has been demonstrated, further papers can address the special challenges of the depiction of armed melee combat and improve on and add to the exercises developed as part of this paper. Though other additions are possible, the following steps are likely the next avenues of improvement and necessary to implement in order.

4.3.1. Detailed Technique Evaluation

One possible follow-up paper could concern the detailed evaluation of the user's technique. This paper uses relatively simple methods to determine the viability and historicity of users' fencing. The only used data is the tracking provided by the tangible. A more in-depth analysis would rely on full-body tracking to determine aspects such as body mechanics and correct footwork, and analyze striking techniques, not just at the point of impact, but during the entire motion, possibly building on previous work utilizing neural networks [al21] or motion capture techniques [al20a].

4.3.2. Physically Simulated Interactions

Another possible follow-up paper could work on fully physically simulated interactions. This paper, due to its limited scope, does not simulate the sword as a physical object in the virtual world, and thus cannot depict fencing techniques relying on swords interacting with each other, such as *Winden* or many of the *Meisterhaue*. A physically based approach would need to evaluate the forces acting on the swords, while taking into account their functionality as levers, as well as the changing relative strength of the user due to body mechanics in different poses.

4.3.3. Force Feedback

Once the digital representation of the swords includes all the forces acting on it, these forces can be translated to haptic feedback in a follow-up paper. A special challenge resulting from historical fencing is the need for a strong directional force at varying points along the blade and in a large volume around the user. Without this force, some techniques which rely on the redirection of an opponent's blade cannot be performed. Haptics which merely make use of vibrations and force impulses along predefined axis may not be enough to achieve the desired result. A near perfect, though impractical, result could theoretically be achieved through the use of an industrial scale robotic arm controlling the tangible's movement.

4.3.4. Virtual Sparring with Reactive Opponents

Finally, once all the challenges inherent to the usage of VR for the training of HEMA have been addressed, fully interactive sparring can be achieved. This can take the form of online multiplayer with multiple users. It may also take the form of computer controlled opponents, as can often be seen in commercially available VR games depicting fencing. The opponent's decision making process could possibly use artificial intelligence techniques as simple as decision trees, as such trees already exist in HEMA training manuals [Aba08, p.127].

Should a long term project ever reach this stage of research development, then the resulting application would be nearly indistinguishable from actual historical fencing in a combat situation. For now the viability of this idea must first be evaluated through a proof-of-concept application and tangible, as described in Section 4.2.

5. Sword Tangible

5.1. Tangibles

The tangible is the user's main method of interaction with the virtual world. In order to interact with the application, the tangible needs to track its own position and rotation in 3D space, and possibly provide feedback, such as haptics to the user. These aspects are taken care of by the off-the-shelf controller of a *HTC Vive*. It is this chapter's goal to incorporate such a controller into a larger tangible replicating a longsword. It is critical that the tangible is functionally identical to historical swords. There are two main areas of interest: the shape of the parts of the sword a user will touch and the overall handling, i.e. the perceived weight and agility of the sword. Both aspects need to be a precise match to existing historical swords.

5.2. Historical Swords

The tangible needs to match historical longswords as closely as possible. Therefore, they have to be examined in detail. First of all, it is necessary to exactly define, which swords are to be imitated. The fencing techniques, which are depicted in this paper, are meant for a type of bladed weapon called the longsword. This name is loosely identical to the terms bastard sword and hand-and-a-half sword. They are defined by their usage of predominantly two hands, while excluding particularly large swords known as greatswords. This definition is imprecise and does not provide much insight. Consequently, additional categorization is needed.

5.2.1. Oakeshott Typology

There is no universal and exact classification for different sword types. This is in part due to the fact there was no culture of precise academic definitions in medieval times. Bladed weapons were typically not given exact terms, but merely referred to as "swords". There have been multiple attempts to remedy this by modern academics. Perhaps the most widely known system is the *Oakeshott Typology*, which categorizes swords mostly based on visual similarity of individual parts [Oak64].

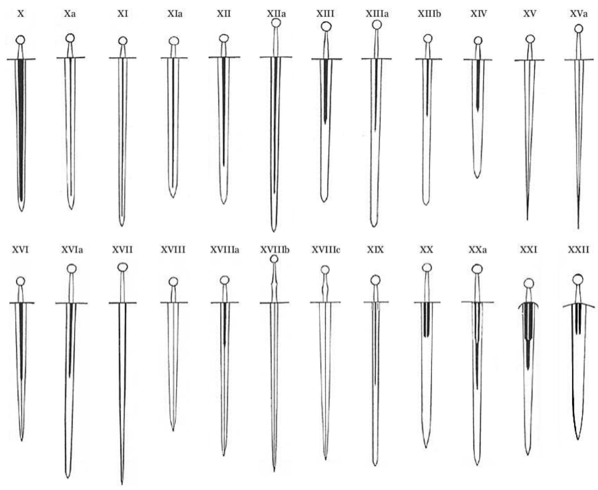


Figure 5.1.: Sword Types as Described by the Oakeshott Typology [Oak91] [Oak64, p.24]

In Ewart Oakeshott's typology there are multiple types, which might commonly be referred to as longswords, such as type XIIa (12a), XVIIIb (18b), and XXa (20a). The type XVa (15a) is of particular interest, as it is the sword usually depicted in the *Fechtbücher* in the lineage of Johannes Liechtenauer, the 14th century fencing master credited with the German lineage of fencing traditions [NAndg]. It is this longsword type, which serves as the primary reference for our tangible.

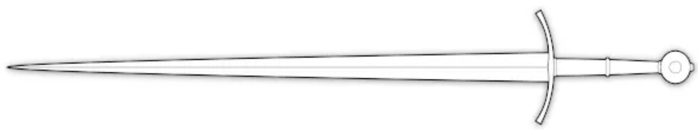


Figure 5.2.: Type XVa Longsword [NAndg]

5.2.2. Reproductions

Since access to historical swords is limited, modern but typically faithful reproductions, such as the ones depicted in Figure 5.3, must serve as additional references. These reproductions are what is usually used in HEMA training. Therefore, they are the ones which need to examined most closely as reference for the tangible. It is their measurements which the tangible is based on, both in terms of shape and handling.

Swords designed not as a direct replica of any historical sword, but as a purpose-built training tool, such as the *Rawlings Synthetic Longsword* and the *Purpleheart Armory Indoor Trainer* as seen in Figure 5.4, are especially of interest, as they serve as an example of

Figure 5.3.: Albion Ringeck & Regenyei Talhoffer Sword Reproductions [NAndb] [NAndd]

what characteristics the tangible must fulfill, even if it deviates from historical facts. The *Rawlings* sword, for example, is significantly lighter and more nimble than a real sword would be. It also makes use of a scent stopper type pommel, even though they are not found on type XVa longswords. Yet it is still considered a viable option for historical fencing. The *Indoor Trainer* is purposely much shorter than a real sword, so it can be used within confined spaces. This concept also applies to the tangible, as the play area in VR is typically only a few square meters and the full length of the blade is not needed for virtual solo-training.

Figure 5.4.: Red Dragon Rawlings Synthetic & Purpleheart Armory Indoor Trainer Longswords [NAndc] [NAnda]

5.3. Physics

5.3.1. Sword Dynamics

In order to create a convincing tangible, it must behave identically to a real sword, when handled by the player. As mentioned in Subsection 2.2.2, research on sword handling has been done. This section of the paper combines Turner's and Chevalier's work and re-contextualizes it for usage on a tangible, only explicitly citing when their approaches differ or exceed fundamental knowledge in the field of physics [Che19] [Tur02].

The handling of a sword is defined by a few key characteristics. Together they allow the quantification and comparison of a sword's perceived weight and agility. The tangible must match these characteristics closely, in order to handle immersively. The main aspects to analyze are [Che19, p.4f][Fölnd, chapter 12.4.2]:

- Total Mass m
- Center of Mass COM
- Moment of Inertia I
- Radius of Gyration r_g

As simplification, the sword is represented as a system of multiple weights $w_i \in W$ of mass m_i at a distance to the COM, known as radius of r_i, with the total number of weights given by $|W|$.

The perceived weight of a sword is determined mostly by the total mass m of the sword. It affects the handling as a resistance to movement. A heavy sword requires more effort to accelerate. In a mass-system, the total mass is calculated by the sum of the masses of all the weights.

$$m := \sum_{i=0}^{|W|} m_i$$

The perceived agility and balance is affected by both the COM and the Moment of Inertia I. The COM is the point the sword is easiest to rotate around, as all rigid bodies naturally rotate around it. When it is far away from the intended axis of rotation, additional force needs to be applied in order to rotate around the intended axis. Therefore a sword with the COM close to the hilt is easier to rotate than one with a balance point closer to the tip. The COM is determined by the weighted average position of the masses.

$$COM := \frac{\sum_{i=0}^{|W|} m_i \cdot r_i}{m}$$

The inertia I affects the handling of the swords in matters of rotation. A high inertia makes the sword more difficult to turn. Similar to the mass, the total moment of inertia is the sum of the inertia of all the weights. The weights' inertia I_i can be simplified as either an infinitely small point-mass, or a thin rod.

$$I := \sum_{i=0}^{|W|} I_i, \qquad I_{i-POINT} := m_i \cdot r_i^2, \qquad I_{i-ROD} := \frac{m \cdot L^2}{12}$$

with the radius r_i denoting the mass' distance from the COM and L giving the length of the rod.

Notably the moment of inertia of a sword is dependent on the axis of rotation chosen for the analysis. Typically, the COM is chosen as the axis of rotation when examining rigid bodies. It may be necessary to calculate the inertia of a mass around another axis I_{AXIS}, such as the grip, at a distance d to the old axis, using the parallel axis theorem a.k.a. Steiner's theorem.

$$I_{AXIS} = I_{COM} + m_i \cdot d^2$$

Finally, the radius of gyration r_g is a way to conveniently encapsulate two other dynamic properties of the sword: the total mass and the moment of inertia. In effect, it describes the overall agility of the sword. It measures the distance a single point-mass would need to the axis of rotation in order to achieve the same moment of inertia as the entire system.

$$r_g = \sqrt{\frac{I}{m}}$$

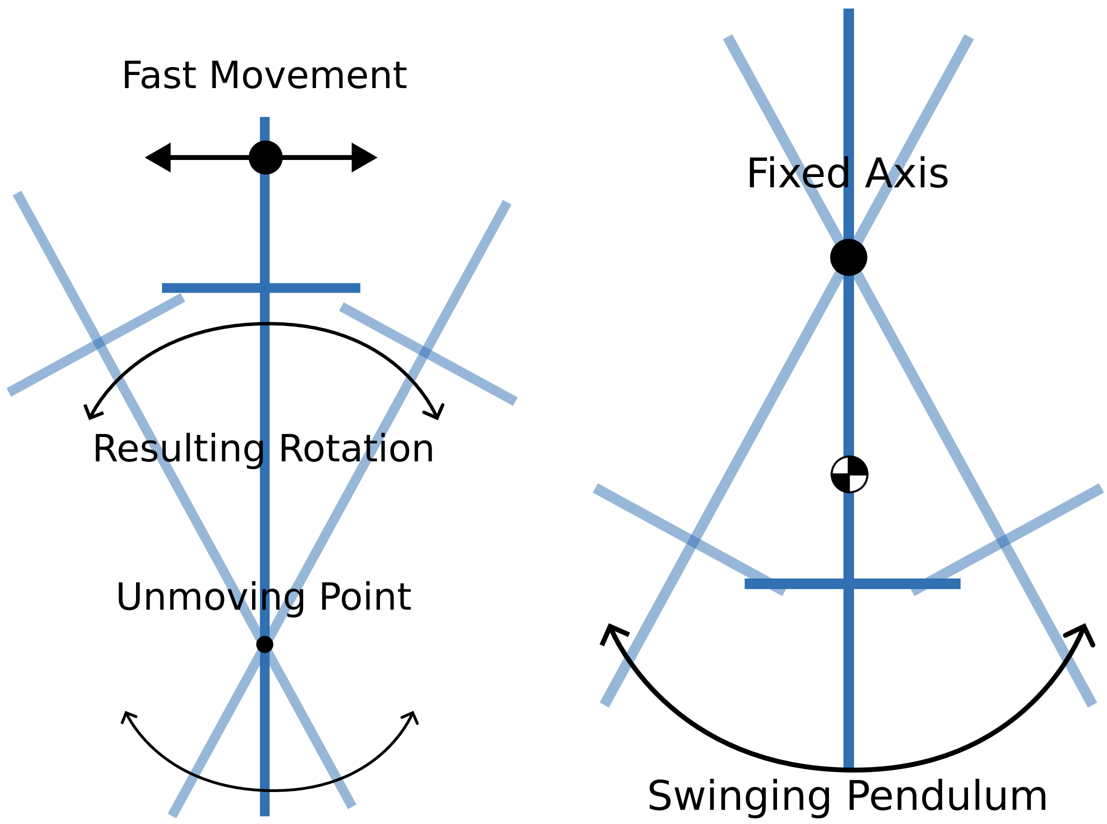
5.3.2. Measuring Sword Dynamics

Most of the sword's properties can be measured trivially: the mass using a scale and the center of mass by moving the sword on a thin rod until it naturally balances. The radius of gyration and by extension the moment of inertia need more attention. Its method of measurement investigates the sword's resistance to rotation.

Waggle Test

The simplest method of determining the radius of gyration is by examining the sword's centers of oscillation, commonly referred to as the waggle test [Che19, p.5][Che14, p.6]. It examines the resulting rotation when a force is applied off-center on the sword. In the test, a sword is pinched at a random point and then quickly moved back and forth.

Consequently, another point on the blade seems to stand still, as it is the center of the resulting rotation. Both points are then noted and later used for computation, as discussed in Subsubsection 5.3.2. The waggle test is fairly inaccurate due to human error, as it relies on negligible interference by friction from holding the sword and a high accuracy when visually determining the center of rotation.



Waggle Test

Pendulum Test

Figure 5.5.: Both Sword Dynamics Measurement Methods

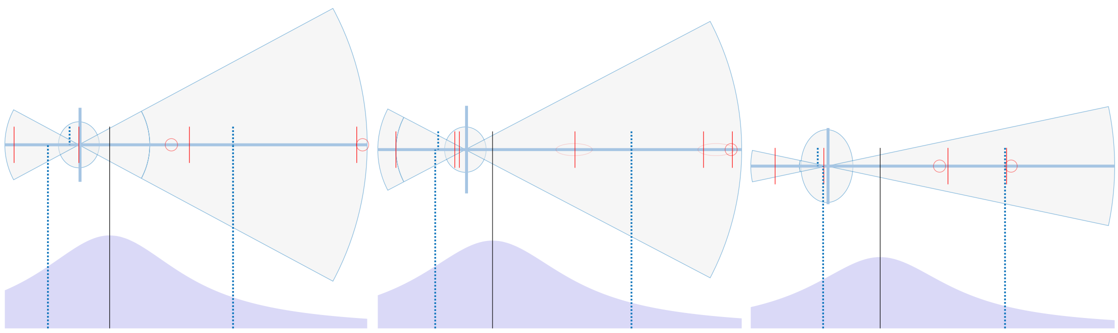
Pendulum Test

The gravity pendulum method, also known as the pendulum test [Tur02, p.148][Che19, p.6][Chend] is generally more accurate, as it is less prone to human error. It entails some overhead, due to its more complicated experimental setup. The pendulum test examines the sword's reaction to gravity, when used as a pendulum. The sword is placed in a sling of variable length, and fixed on a thin edge acting as the axis of rotation.

Then the sword is slightly lifted and released, so it begins to swing. The period of a swing, as well as the chosen axis is recorded and later used in the calculations. The equations used are explained in detail in Turner's paper [Tur02], but not relevant to this paper.

Weapon Dynamics Computer

The process of measuring and calculating the dynamic properties of a sword is greatly simplified by the *Weapons Dynamic Computer* [Vin], created by Vincent Le Chevalier and Peter Johnsson. It explains the procedure of the experiments and automatically calculates the results. Conveniently, it also generates diagrams allowing the comparison of swords' dynamics at a single glance. This ease of use contributes to the crowd-sourcing of data from both, surviving antique swords and commercial sword replicas, even by non-academic sources [NA16].



Albion Ringeck   Regenyei Type XVa   Albion Gallowglass

Figure 5.6.: Crowd-Sourced Data of Sword Replicas [NA16]

The generated diagrams are easy to read, even though they may at first glance seem complicated. The red markings and dashed lines are not relevant for the purposes of this paper. The curve at the bottom shows the effective/perceived mass distribution along the sword. The black line represents the *COM*. The ellipse at the crossguard shows the agility of the sword in terms of movement, and the hourglass in terms of rotation, with larger areas indicating a more nimble sword.

5.3.3. Mimicking Sword Dynamics

In order to mimic the dynamics of a sword, the tangible's parts need to be a mass-system whose weights combine to closely match the given properties. Determining the needed masses in a system with many weights can be exceedingly complicated to do by hand, as the resulting system of equations has a multitude of solutions, due to the high number of unknown variables.

$$\begin{bmatrix} m \\ \\ COM \\ \\ I \end{bmatrix} = \begin{bmatrix} \sum_{i=0}^{|W|} m_i \\ \\ \frac{\sum_{i=0}^{|W|} m_i \cdot r_i}{m} \\ \\ \sum_{i=0}^{|W|} I_i \end{bmatrix} = \begin{bmatrix} m_1 + m_2 + m_3 + m_4 + ... \\ \\ \frac{m_1 \cdot r_1 + m_2 \cdot r_2 + ...}{m_1 + m_2 + m_3 + m_4 + ...} \\ \\ (m_1 \cdot r_1 + m_1 \cdot d_1^2) + ... \end{bmatrix}$$

Swords as a Two-Mass System

Luckily this problem can be simplified, as there always exists a solution to the equation system with just two weights [Che14]. If one weight is assigned a fixed position r_1, then the second weight's position r_2 and both masses m_1 & m_2 can be determined easily. There are two main options for a fixed position. Chevalier chose the crossguard, because the resulting weights for this position can be trivially determined by his version of the waggle test [Che14]. Turner chose the pommel as a more convenient mounting place for the main weight, presumably because it results in a more even spread of the total mass between the weights [Tur02].

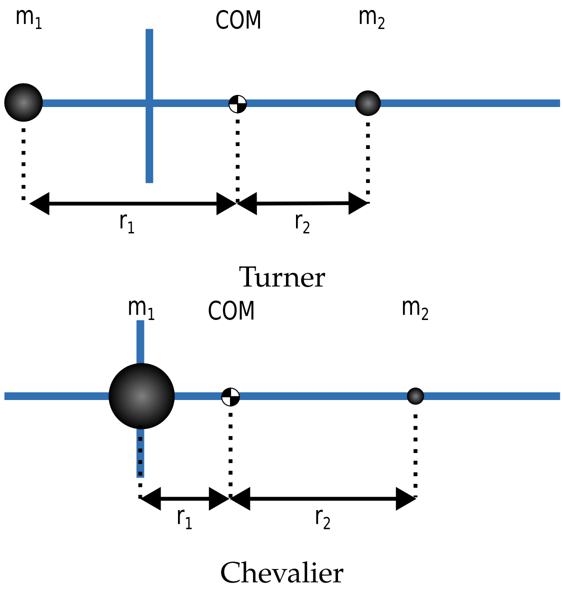


Figure 5.7.: Two Approaches for Swords as a Two-Mass System

Calculation of Weights

In reality other weights also need to be included in the system, in order to connect the two main weights to a solid, sword shaped base. Turner includes such a third weight in the form of a thin rod of known length. The tangible needs to be as compact as possible, but no longer than necessary to mount the second weight at r_2. This complicates the process as the length of the rod is treated as a fixed value affecting the other results, but in our case is undetermined until the positions of the weights are known. An iterative process can be used to remedy this issue. Consequently, our method extends Turner's approach. It consists of four main steps:

1. Calculate preliminary weights using Turner's approach [Tur02, p.16]
2. Design and build a base able to support the weights
3. Measure the dynamic properties of the base
4. Calculate new weights based on this information

The last two steps need further explanation. The base's dynamic properties can either be measured like any other sword's as described in Subsection 5.3.2, or they can be determined analytically, using the equations discussed in Subsection 5.3.1, if all of the used parts are well known. The last step then uses these values instead of the values given for the rod in Turner's approach. This approach requires an in-depth break-down, since Turner's explanation is fairly detail focused, instead of providing an abstract understanding of the issue.

First all measurements need to be converted into a single coordinate system. Choosing the end of the sword as the origin of the axis is particularly useful, as it avoids negative values for positions. Alternatively one might choose the COM as the zero position, making the calculation of the distance to the COM trivial. Also all measurements should be converted to base SI-units: meters and kilograms. Often the moment of inertia may not be known directly, with the data only containing the radius of gyration. Using its definition, r_g can be calculated trivially from the inertia and mass.

Secondly the mass m_{BASE}, balance point COM_{BASE} and moment of inertia I_{BASE} of the base, to which the other weights are mounted, need to be calculated, if not determined through measurement. The mass and balance point can be computed trivially per their definitions. The moment of inertia requires more attention. First, if not represented by a point mass, the inertia I_{i-SELF} of parts around their own center of mass should be calculated. Then using the parallel axis theorem, the inertia I_{i-AXIS} around the chosen axis of rotation is calculated. Use I_{i-AXIS} in the sum for the total inertia of the base I_{BASE}.

Thirdly, the masses of the two weights, fixed to the base-mount, can be determined. Since the desired balance point is typically close to the hilt, the pommel's mass at a distance of r_1 to COM needs to be supplemented by a balance mass $m_{BALANCE}$, in order to make up for the difference in COM_{BASE} and COM_{SWORD}.

$$m_{BALANCE} := m_{BASE} \cdot \frac{COM_{BASE} - r_1}{r_1}$$

The total mass m of the system is still lower than the desired m_{SWORD}. The outstanding mass $m_{ADDITIONAL}$ can be calculated trivially, given the two existing weights.

$$m_{ADDITIONAL} := m_{SWORD} - (m_{base} + m_{m_{BALANCE}})$$

The inertia I_{BASE} of the base is also not yet sufficient. The needed additional inertia $I_{ADDITIONAL}$ is determined similarly, while compensating for distance between the different axes of rotation.

$$I_{ADDITIONAL} := I_{SWORD} - (I_{BASE} \cdot r_1^2)$$

Using this information the remaining mass $m_{ADDITIONAL}$ can be divided between the pommel m_1 and tip-weight m_2, in order to reach the desired moment of inertia, while keeping the correct COM.

$$m_1 := \frac{m_{ADDITIONAL}}{\frac{m_{ADDITIONAL} \cdot r_1}{I_{ADDITIONAL}} + 1} + m_{BALANCE} \qquad m_2 := m_{ADDITIONAL} - m_1$$

with the weight at the tip of the sword at a distance r_2 to the COM, crucially different from the position p_2 relative to the coordinate system.

$$r_2 := \frac{(m_2 - m_{BALANCE}) \cdot r_1}{m_2} \qquad p_2 := r_2 + COM$$

As part of our work we automated this entire process through a *Python* script, allowing for quick iteration of prototypes without arduous manual computation, along with easy conversion of data between Chevalier's and Turner's approach. In the future, the script may need adjustment for other use cases, as it is tailor-made to support the parts used in our prototypes.

5.3.4. Practical Limitations

The tangible needs to be considerably shorter than full length swords, as it needs to be used indoors, where low modern ceilings and limited space limits the safe area a user can move around and swing in. Consequently, the weights need to adjust for the smaller base. Therefore, both the tip and pommel weights need to increase accordingly. While this is easy to accomplish with the tip weight, there are some problems increasing the pommel's mass considerably higher than historical levels. Since the shape and size need to stay consistent, the density may need to be adjusted through the use of a different metal. This, like any metal manufacturing, is beyond the scope of this paper. Instead, a fixed weight steel pommel, originally intended for the Red Dragon Rawlings Synthetic Longsword, is used. This limitation to preexisting pommels of insufficient weight inevitably leads to either an incorrect balance point or moment of inertia, depending on if the extra mass is added to the base or the tip weight. The calculations are easily adjusted by setting a fixed value for m_1, but the underlying issue needs to be addressed to achieve fully accurate sword dynamics. However, modifying the base of the tangible to be comparatively heavy, mitigates the issue, as the resulting ideal weights are close to the fixed pommel weight.

5.4. Prototypes

5.4.1. Version 1 - Two-Handed Interaction

Not all the prototypes are created with the correct sword dynamics in mind. Instead, the prototypes iteratively improve and add features to slowly approach the envisioned tangible. The first prototype is merely intended to facilitate early tests of the software side of the project. As such it does not need to perfectly match a real sword in every aspect. Its main purpose is to provide the main method of interaction with the virtual world, critically placing both hands on the tangible, without access to the VR-controller's buttons.

A simple wooden handle with a crossguard and a mount for the controller used for tracking is sufficient for the purposes of the first prototype. The two-handed interaction methods prove viable and allow the user to perform basic fencing techniques, though the first prototype feels very different from an actual sword, both in terms of shape and handling. This prototype also reveals the importance of a secure mount of the controller, as quick movements result in considerable centrifugal force, launching and possibly damaging the controller and surroundings.

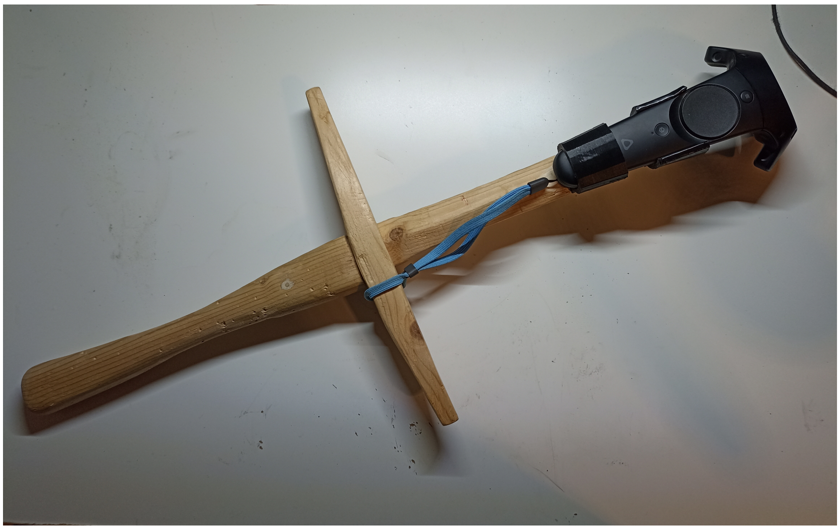


Figure 5.8.: Tangible Prototype 1 - A Simple Mount for the Controller

5.4.2. Version 2 - Historical Shape and Feel

Version 2 seeks to address the lessons learned from the first prototype. The shape of the prototype matches historical swords closely. The pommel and crossguard are off-the-shelf parts from the *Red Dragon Rawlings Snythetic Training Longsword*, as the manufacture of thin, robust and heavy parts is outside the scope of this paper. The base on which the parts are mounted is handmade out of spruce wood, and shaped using woodworking tools, such as a belt sander and draw knife. The shape of the hilt is based on measurements from the training longsword, closely matching historical swords. The controller mount is redesigned with a front plate, preventing the controller from sliding off the tip.

The shape of the prototype is correct, but the handling is considerably lighter, because the low mass of the wooden base would require exceptionally heavy weights to balance correctly. Warping and twisting of the wood, as well as inaccuracies caused by the handmade nature, create potential issues when aligning the tangible with its virtual representation. Additionally, the high workload and required woodworking skill needed to produce a well-shaped base, make this approach unsuitable for rapid prototyping. Furthermore, the mounting method requiring nails damages the prototype considerably when varying weight-placement, making experimentation, as well as the repeated removal of the controller, non-viable.

Figure 5.9.: Tangible Prototype 2 - Wooden Sword with Weights

5.4.3. Version 3 - A Modular Construction Approach

The third prototype utilizes an alternative construction method based on 3D-printing (additive manufacturing), in order to fix the encountered issues regarding the manual manufacturing process. It allows for fast changes to individual parts, without requiring a laborious rebuilding of the entire base. Instead, the parts are mounted on a standard M8 galvanized steel threaded rod and secured using nuts. The individual parts, such as the controller mount, are printed from PLA plastic. The 3D-printer allows the creation of more complex shapes than would be possible to create by an untrained woodworker. The grip for example is a waisted hilt with a ring riser for a more ergonomic and historical user experience. The shape is based on a replacement part for the training longsword [Mal17], but has been completely remodeled to reach the standards required of 3D-assets used in video games, so the model can be reused in the application, achieving a perfect match between tangible and game geometry.

Figure 5.10.: Tangible Prototype 3 - 3D Printed Parts on a Steel Bar

The threaded rod, while allowing for good prototype iteration, has a too low bending stiffness to support the controller and tip weight in use at full speed. The galvanized steel wobbles noticeably and eventually bends permanently, making accurate tracking of the tangible's third prototype impossible long term. The issue is further confounded by the unidirectional nature of the rod combined with nuts as a mounting method, making mistakes in the tracker placement's rotation frequent.

5.4.4. Version 4 - Structural Stability

The issues in structural instability and inconsistent controller mounting placement can both be solved by an additional support structure. Interlocking segments are placed along the blade and secured using nuts. They constrain the controller's rotation to the rotation of the crossguard, which is linked to the grip, locking the entire sword together along its axis. This prevents the tangible from becoming a source of error for edge alignment issues in the application. It also reinforces the steel rod along the sword's leading edge, providing much-needed extra stability. It should however be noted, that these structural parts, as well as all the used 3D-printed parts, should not be printed using standard settings, but instead have an outer shell of at least 5 layers and an infill of no less than 30%, to improve the parts' strength, as PLA-plastic is a brittle material.

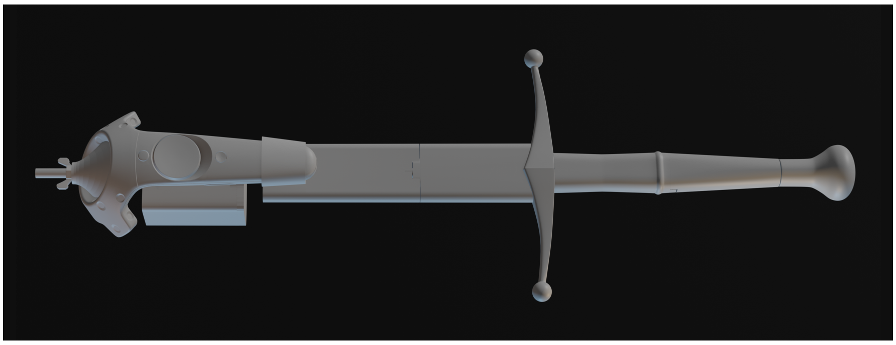


Figure 5.11.: A Digital Render of Prototype 4 of the Tangible

Figure 5.12.: Tangible Prototype 4 - Structurally Reinforced and Balanced

This final prototype fixes all the previously addressed issues. Consequently, the process for correct balancing, explained in Subsubsection 5.3.3 is used to achieve a tangible with handling comparable to a historical longsword. The list of parts Table 5.1 provides the values used for the calculations . The tip weight is realized through a 3D-printed box, making the change of it's mass easy. It should be noted, that its mass is 200 g less than the calculated amount, because as a simplification the controller is considered part of it. The pommel also slightly differs from the optimal mass, as it is an off-the-shelf part.

Part	Length	Weight	Position	Price
Steel Pommel	5 cm	458 g	0 cm	30 €
Waisted Grip	20 cm	96 g	10 cm	
Crossguard	24 cm	40 g	20 cm	8.90 €
Struct. 1	11 cm	53 g	25.5 cm	
Struct. 2	14 cm	65 g	36.5 cm	
Mount 1	4 cm	23 g	43.5 cm	
Box (w. Lid)	5.5 cm	84 g	51 cm	
Box Weight	5.5 cm	ca. 168 g	51 cm	
Controller	12 cm	200 g	51 cm	
Mount 2	4 cm	26 g	55.5 cm	
Nuts		5 g ea.		
M8 Rod	66 cm	200 g		
PLA Plastic		ca. 600 g		ca. 10 €
Total	70 cm	1464 g		ca. 60 €

Table 5.1.: List of Parts Used for Prototype 4 of the Tangible

6. Application Development

The actual implementation of the application is accomplished by tried and tested software development techniques. For 3D-asset creation *Blender* is utilized, because of its breadth of features and open-source nature. As a game engine *Unity* is used, because of its user-friendliness and native VR support. Additionally Valve's *Steam VR* plug-in is used to provide optimal integration with their HMDs.

6.1. Choice of VR Headset

The choice of VR HMD typically also entails the choice of utilized tracking technology for the tangible. This tracking technology must be able to handle the unusual circumstances, which the typical movements in historical fencing entail. The tracker on the tangible may spend large amounts of time outside the field of vision of the user, as the *Huten* often place the sword above the head, next to the fencer's hips or even behind their back. This may become an issue for some VR systems, which employ inertial sensing when outside the user's field of view, as part of their inside-out tracking technology. These inertial methods are typically less robust than other technologies. To avoid potential tracking issues, VR HMDs, such as the *HTC Vive* and *Vive Pro* should be considered, as they rely on optical sensing instead. Unfortunately this comes with the drawback of limited and predefined play area bounds, constrained by the placement of fixed external sensors.

6.2. Choice of Exercises

The choice of exercises is strongly limited by the scope of the proof-of-concept nature of the application. As the application needs to be usable by laymen, it needs to teach the fundamentals of historical fencing. As a result, one of the exercises must inevitably be some sort of technique instruction, teaching the basics of *Huten*. Since full-body tracking is outside the scope of this paper, footwork exercises cannot be part of this introduction. Building on these basics, users must also be taught how to correctly attack. This can be extended to a flow-drill.

The lack of haptic feedback prevents a convincing, and therefore useful, depiction of blade-on-blade contact. As a result such techniques, which go beyond the initial attack, the *Zufechten*, cannot be used. Blocking attacks, the next sensible step, is therefore also not possible. This limitation excludes many of the advanced techniques, such as any possible *Winden* and most multi-step exercises. The exception to this is the *Nachreißen*, which does not require any haptic feedback as the initial attack is dodged, but does teach the important concepts of *Indes*-timing and *Mensur*.

As the exercises need to follow a sensible learning-curve, the technique introduction is best placed first, followed by a clarification on correct cutting technique, and ending with an advanced exercise such as a flow-drill or *Nachreißen*. This should teach core concepts, such as the *Vier Blößen*, *Huten*, importance of proper technique, timing, and distance. More advanced techniques are left to future additions beyond the scope of this paper.

6.3. Introductory Exercise

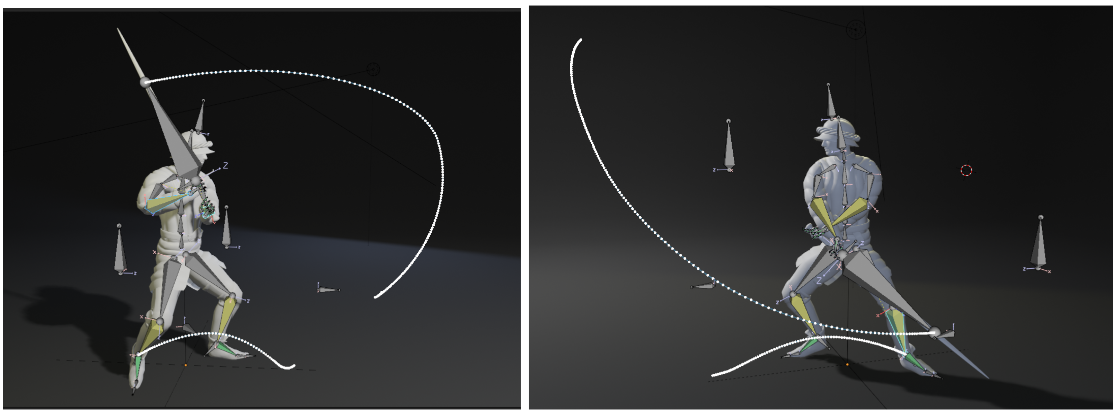
The *Huten* and attack introduction consists of characters showing the correct poses and a series of instructions on how to properly perform the depicted techniques. The instructions need to explain the concept of *Huten* as nodes in movement. The example characters need to demonstrate this concept interactively. The chosen method for this is to have the characters first show the *Huten* in isolation, then slowly move between them and finally use them while performing a proper attack technique. This should provide an intuitive understanding of how to interpret *Huten* as movements, even outside of VR. Since the user needs to follow along with the techniques, the easiest attacks should be selected. The *Oberhau* is the most intuitive to perform. It is the most natural of movements, being aided by the human body's bio-mechanics. It is also the starting point of many of the more complex sequences shown in *Fechtbüchern*. If supplemented by the *Unterhau*, all of the four openings are covered, giving an implicit understanding of them.

Figure 6.1.: Technique Introduction Exercise in Game

6.3.1. Animations

The introduction requires characters performing historical attack techniques. This is possible through animations. Many animations depicting the use of two-handed swords are commercially available. These are however typically not at all historical. The *Longsword Animset*, by Kubold [Kub17] is an exception to this, which is why it served as a place-holder during early versions of the application. It does however suffer from the same extreme visual amplification of actual movements for the purpose of gamification, making it not useful for the teaching of actual techniques. In the attempt to create custom animations, avenues for motion capture using consumer-level equipment were explored. Both versions of the widely available Microsoft Kinect depth camera are popular options for this. Unfortunately the generated data is not stable enough to be used directly, especially in situations, where the arms cross or are obscured by the body. The animations provide a good source of timing, but require a large amount of manual clean-up before they become usable. As this effort is needed either way, animations were created fully manually. In animation important poses, so-called key frames, are typically used as corner stones to base the rest of the animations around. This concept aligns neatly with *Huten* as nodes of movements. Therefore, the careful posing of *Huten* as key frames allows for a comparatively easy and crucially historically accurate creation of animations. The resulting movement is somewhat stiff, as the typical approaches used to emphasize movement [NAndh], are often detrimental to correct technique. For example the principle of animation known as anticipation, is called telegraphing in martial arts and deemed an error to be avoided, as it provides information to the opponent, allowing them to dodge easily.

Figure 6.2.: The Huten Used as Key Frames for Manual Animation



Oberhau Unterhau

Figure 6.3.: Animations for the Oberhau and Unterhau Attacks

6.3.2. Player Performance Evaluation

Performing techniques correctly, even when merely assuming a *Hut*, requires precise positioning. The application can determine if the sword is correctly placed, due to its tracked data, but it cannot determine the correct positioning of the body, due to the lack of full-body tracking. As a result there is relatively little information on the user's performance in this exercise. Evaluating the player based on their swords placement is possible, but might lead to false positives, where the sword is correct, but the rest of the body is incorrect. This would lead to the reinforcement of incorrect behavior, thereby misleading the user. Consequently, the application does not evaluate or give feedback on the users performance during this exercise.

6.3.3. Comparison with Real Life Exercise

When comparing the introductory exercise to traditional training methods, a distinction between solo-practice and group training must be made. When training alone, it can be difficult to correctly interpret the historical illustrations or even modern training-videos. The lack of depth perception and limitation to a single viewpoint can hinder understanding of the showcased techniques. These issues are being addressed and mostly solved by this application. Users can view the example characters from any angle, as close up as they wish. The lack of feedback about the user's performance is however a detriment. When practicing HEMA in a group environment, more experienced fencers can give real-time feedback and actionable suggestions for improvement.

6.4. Tatami Cutting Exercise

The tatami cutting exercise consists of a target, which is to be cut into multiple pieces by the user. It trains correct cutting technique. It also fits well into the scope of this proof-of-concept application, as it does not require strong haptic feedback or any kind of complex blade-on-blade interaction. It is not part of historical medieval or renaissance swordsmanship, but developed out of Japanese lineages of swordsmanship [NAnde]. This caveat is and needs to be stated clearly, in order to not mislead users about history. Yet it is the primary method of evaluating proper cutting technique in HEMA, possibly because it is both more informative and satisfying than striking drills using blunt swords against more robust targets.

Figure 6.4.: Tatami Exercise in Game

6.4.1. Mesh Slicing

The digital cutting of objects along a plane is a solved problem in the field of geometry processing. It is known as mesh slicing. Consequently, there are many freely available implementations of it online. The chosen version is an adaption of a comprehensive write-up by SMOOTHSLERP [SMO21]. Their implementation takes the input coordinates of the slicing plane only in the local object-space coordinate system. This issue can easily be corrected by means of the *Unity* game engine's built-in conversion functions. Once the target object has been cut into two objects, both of them need to be fitted with the slicing and physics functionality. Importantly, since during these calculations the sword is still in contact with both of the new sub-targets, they need to have all functionality paused during a cooldown period, in order to avoid false positives in the collision detection, causing objects to be hit multiple times.

6.4.2. Player Performance Evaluation

The evaluated technique in the tatami exercise is the cut. In order to cut any target using a sword, proper technique must be employed. Determining which attacks are valid is a complex process. There are two main approaches. The physically based approach aims to accurately model the target mathematically and draw conclusions based on numerical data. The analytical approach determines success based on observed rules-of-thumb. This process is less accurate, but allows finer control of the application's difficulty and makes it possible to give actionable feedback to the user.

Physically Based Approach

There are multiple physical approaches used to evaluate a cut. They typically calculate how deep a cut could theoretically penetrate, based on resistance, fluid friction or imposed blade drag [Che17] [Fra18b]. They usually neglect factors directly related to user error, such as edge alignment, and also assume all physical properties of the target object be known. Generally, the state of research has not yet reached the point, where the physically based approach can be used to evaluate technique. Sean Franklin, a renowned HEMA practitioner and researcher agrees with this assessment:

> "Cutting with swords is still a field which has not had an abundance of serious research [...]. And, alas, this means that we can only start drawing a few dots back to our own practice, rather than understand sword cutting wholesale from existing research. [...]"
> - Sean Franklin (Sword STEM)[Fra21]

Analytical Approach

The analytical approach of evaluating cutting technique relies on defining a rule-set of what constitutes a good cut, based on empirical observations. These rules can be extrapolated from the advice given by experienced fencers, as well as the rule-sets of modern tournaments, which also employ this analytical approach.

> "Some modern reenactors, lacking experience in handling actual antique weapons or cutting extensively with accurate reproductions, have asserted that effective cuts always require a pulling or "drawing" action commensurate with the blow. While with a straight blade such an element is an inherent part of any cut (just as is focus, edge placement, grip, velocity, force, and proper coordinated body motion to follow through), it is unmistakably not a factor in [effective cutting] [...]. The sharper the edge, the stronger or faster the blow, and the more precise the angulation of the impact all make a difference in the effectiveness of a sword cut. However, there can be no question that powerful and effective cuts using straight blades are easily performed without any appreciative drawing or slicing action."
> - John Clements (ARMA) [Clend]

This quote by John Clements, of the Association for Renaissance Martial Arts, gives the following factors, notably excluding a drawing/pushing motion:

- Focus
- Edge placement
- Grip
- Velocity
- Force
- Body mechanics

HEMA tournament rule-sets regarding strike validity are varied, but often similar to the ones laid out by Battle born HEMA [NA24b]:

- Both hands on the weapon
- Proper edge alignment
- Blade travels over a 45 ° arc

The difference in factors between cutting advice and tournament rules is likely largely due to context and implicit assumptions. For example velocity and body mechanics do not need to be addressed explicitly in a tournament, as the presence of a resisting opponent necessitates them.

Implemented Cut Analysis

The factors of the analysis were determined as a mix between cutting advice, tournament rules and practical limitations. The following factors were chosen to determine strike validity:

- Velocity at impact point
- Edge alignment
- Impact point along the blade

This selection of factors allows concrete actionable feedback and mimics the challenges of actual cutting, while ignoring only factors that cannot be analyzed due to the lack of full-body tracking.

The sword's velocity is perhaps the most important factor. It is calculated from the data provided by the tracker on the tangible, using simple rigid body physics:

$$\vec{v}_{POINT} = \vec{v}_{TRACKER} + \vec{\omega} \times (\vec{p}_{POINT} - \vec{p}_{TRACKER})$$

Experimental data of sword velocities gives peak values between $13\frac{m}{s}$ and $20\frac{m}{s}$ [Fra18a] [Che18]. A minimum speed of $10\frac{m}{s}$ was chosen.

Edge alignment is the congruence between the sword's movement direction and blade orientation. The error in edge alignment is the difference between the two. It is calculated by the angle between the blade and movement plane. There is no concrete data on the maximum edge alignment error in actual test cutting. A maximum angle of 20° was chosen, based on admittedly subjective user testing, in order to keep the application accessible to laymen.

The strike point is the point along the blade, which makes impact with the target. While not explicitly listed in tournament rules, likely assumed to be implicitly understood, it is nonetheless an important factor, influencing both the impact speed, and the distance from the opponent. It also naturally arises from the physical properties of swords, with the optimal impact point being known as the percussion point [Tur02]. Striking with a point along the blade too far from the optimal point hinders a viable cut. As an optimal position $60cm$ from the hilt, with a maximum deviation of $40cm$ was chosen, thus making only the area directly by the hilt unable to cut.

6.4.3. Comparison with Real Life Exercise

The tatami cutting exercise is functionally identical to its real life equivalent. It does however make the process much easier, as less overhead is required. Tatami mat targets do not need to be purchased, prepared and setup, which is both time-consuming and financially straining. The immediate and precise feedback is also an improvement on the real-life version, as with traditional test cutting, the reason for failure can sometimes be unclear.

6.5. Meyer Square Exercise

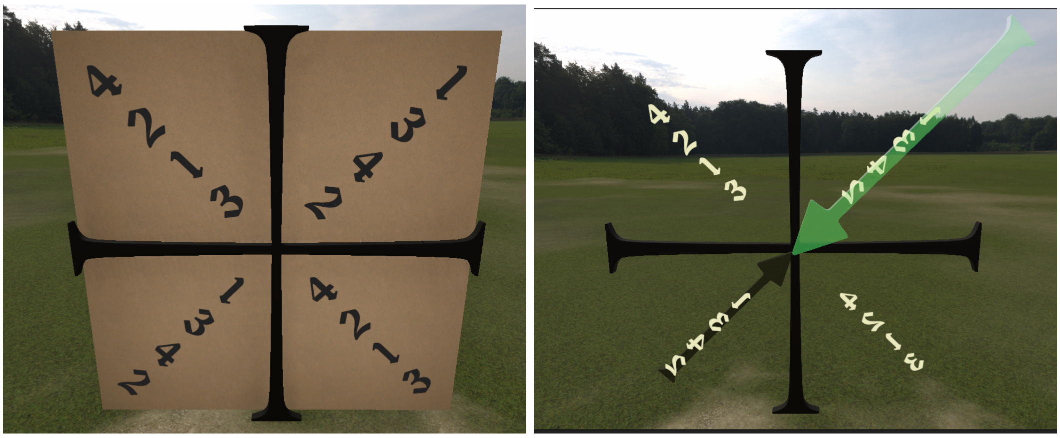
The *Meyer Square* is a historical flow-drill consisting of alternating attacks to the four openings, in order to teach the quick and smooth chaining of cuts. It is a convenient way to transition into more complex motions, beyond basic attacks, while building muscle memory of common attack sequences, whilst still relying only on the fundamental *Oberhau* and *Unterhau*. In the exercise the user stands opposite to a diagram, which instructs them on the correct order of the attacks. The user then performs them as quickly and fluidly as they can.

6.5.1. Player Performance Evaluation

Detecting which openings is being attacked is a simple matter of comparing the direction of the sword's velocity vector to the the four diagonals. The application calculates the attack direction, analogous to the velocity for the Tatami exercise. Then the attack direction is converted to the target's local coordinate space, where it can be compared to four opening diagonal directional vectors. The one with the lowest angle between the opening and attack vector is selected and then associated with a human-readable value. Each time the target is struck, it compares the struck opening to the one expected in the *Meyer Square* sequence. If the correct opening was chosen, the sequence continues with the next one, otherwise feedback on the correct opening is displayed.

6.5.2. The Traditional Meyer Square

The traditional version of the *Meyer Square* is a simple diagram. It takes some effort to decipher. This poses a challenge to newer fencers and can hinder their progress unnecessarily. Neither readability issues, nor memorization are in the interest of this exercise.



Traditional Interactive

Figure 6.5.: Both versions of the Meyer Square

6.5.3. An Interactive Version of the Meyer Square

Interactivity can greatly improve the flow and therefore learning value of this exercise. The application displays both the current opening and the next opening, making the deciphering of the diagram trivial. This way the format of presented information does not slow down the fencers in this speed-focused exercise.

6.6. Nachreißen Exercise

Nachreißen is a historical technique utilizing the timing concept of *Indes*, to dodge an enemy's attack and then counter-attack. It is a convenient way to practice timing and the estimation of *Mensur*, the distance to the opponent. In the exercise an opponent walks towards the player and attacks, once in range. The player needs to take a step backwards to dodge the attack and then deliver their own. This exercise was part of early prototypes of the application, but was not included in the final demo. It requires quick footwork and a good sense of timing and distance. Overall it is too advanced for a layman to learn within the limited scope of the proof-of-concept application. VR does however provide opportunities of improvement over the real-world counterpart of this exercise. It is for example possible to display the opponent's maximum range and pause the action at the critical moment during the exercise, to emphasize the concepts of *Indes* and *Mensur*.

6.7. Usability

To accomplish an overall satisfying user experience, the usability of the application needs to be considered. It is the degree to which users can accomplish their goals, when using the application [Admnd] - in our case navigating it to perform the exercises without issues. This includes issues such as the intuitiveness of the interaction methods, chosen method of information display, and possible safety concerns arising from digital training of a combat sport.

6.7.1. Play Area Bounds Visualization

The high speed usage of a tangible weighing over a kilogram in a tight space provides a safety challenge. In most VR applications it is satisfactory to warn users of potential collisions once they approach the borders of the active play area. In this application that is not sufficient, as users sometimes move at their top speed and the tangible extends a considerable distance in front of them. Therefore the user must continually be made aware, not just of the rectangular bounds of their play area, but of the actual borders of their available space. This is achieved by the means of a procedurally generated fence, which dynamically adjusts to the play area and automatically updates if the play area is recalibrated or recentered. Therefore it represents the limits of the available space more accurately than a standard static bounds visualization, highlighted in blue in Figure 6.6.

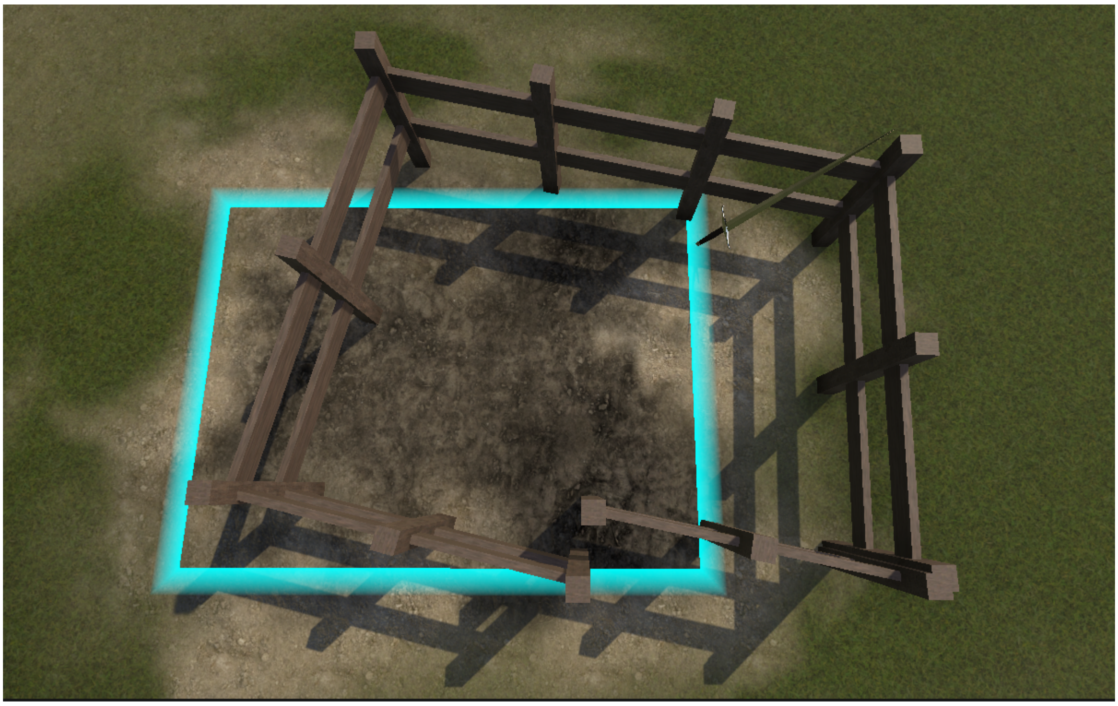


Figure 6.6.: Procedurally Generated Fence Representing Play Area Bounds

6.7.2. Information Display

The application needs to convey a lot of information, both about itself and about concepts of historical fencing. To effectively communicate the instructions, they must be concise and readable. Info-boards are a proven method to achieve this. They provide a better contrasting background for the text than free floating text by itself. Due to their limited space they also force efficient communication of information, through short and succinct paragraphs, where longer more verbose text would likely lose the user's attention. The visuals are made to invoke the style of the historical *Fechtbücher*. The background has a paper texture. The chosen font *Canterbury Regular* is reminiscent of the early 15th century *Ellesmere Manuscript* of the *Canterbury Tales*. It is also visually similar a *Fechtbuch* by Joachim Meyer [Mey70].

Figure 6.7.: Boards with in-Game Instructions and Historical Background Information

6.7.3. VR Menu Navigation

Being a digital application, there is a need for the user to navigate some kind of menu. This allows them to select and reset exercises, and to go through the instructional sequences. To keep the method of interaction consistent throughout the entire application, menu actions are triggered by hitting targets with the sword. This way users always use the same motions for every action, without having to recollect the correct inputs for specific actions. This also allows the tangible to completely ignore the *HTC Vive* controller's buttons, in favor of a user experience closer to wielding an actual sword.

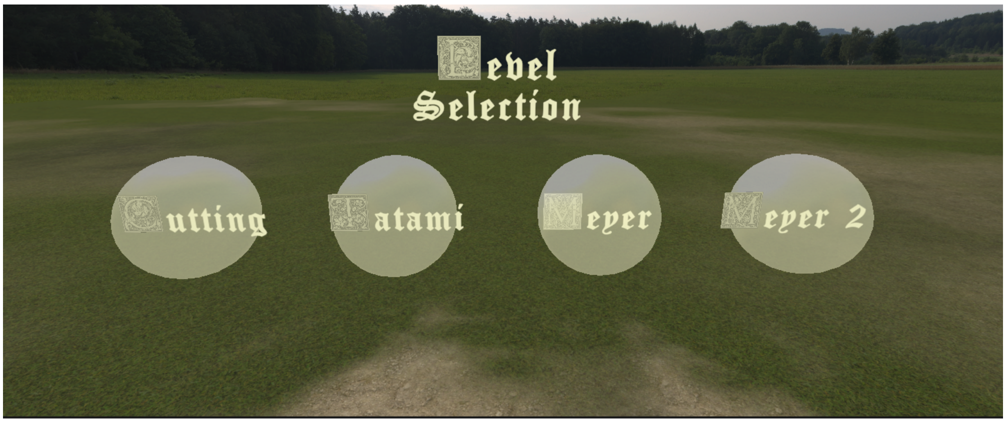


Figure 6.8.: VR Menu Navigation

6.7.4. Interaction Feedback

Offering informative feedback is an important concept of usability and game design. The third of Ben Shneiderman's *Eight Golden Rules of Interface Design* states:

> "For every user action, there should be an interface feedback." [Shn16]

In the interest of consistency, every user action in the application is based on an attack using the sword. Therefore every aspect of the attack must give feedback that is easy to understand. When a cut is analyzed, as described in Subsubsection 6.4.2, an event is invoked, supplying information to other parts of the application, according to reactive programming patterns. The feedback functionalities are handled independently of each other and the struck target.

Feedback Text

The perhaps most obvious, but also most clearly comprehensible method of offering feedback to the user is plain text. In accordance to convention, positive feedback is represented by green, while negative feedback is red. Particularly important or rare feedback is highlighted additionally through the use of a dark background.

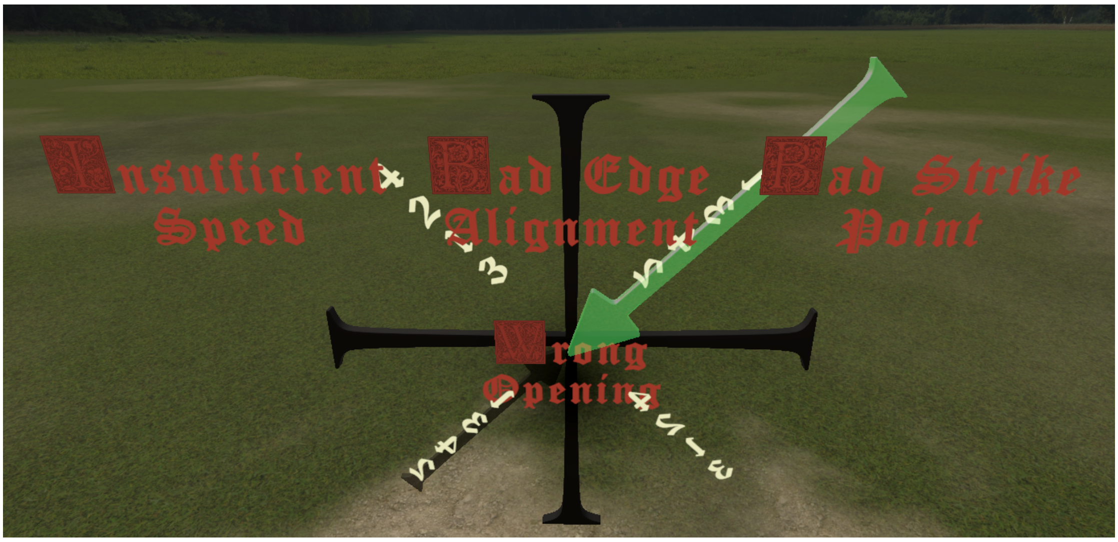


Figure 6.9.: Text Providing Actionable Interactive Feeback

Controller Vibration

Vibration of the tangible is a method often used for haptic feedback. While it cannot convey the complex information of the bind during *Fühlen*, it can convey approximate information about impacts with targets, through the duration and intensity of the vibration. The physically correct frequencies can be calculated - There are two important frequencies inherent to a blade: length-wise and side-to-side, with side-to-side oscillations taking up to $0.12s$ to reach the hand [Tur02, p.134]. Unfortunately, these vibrations are nearly imperceptible, as the standard *HTC Vive* controller does not vibrate strongly enough to affect the tangible. The creation of a stronger custom-built vibration device is out of scope for this paper.

Audio

Sounds subconsciously strongly affect a user's perception of the digital world. In order to further an intuitive understanding of correct technique, different sound clips are played, depending on the validity of the user's attacks. The audio volume is based on strike velocity. Different materials also provide different sound cues when struck. Since accidental hits of the scenery are inevitable in the relatively small play area, only viable targets provide sound cues as to not annoy users.

6.8. Art Assets

All applications need some visual representation. In video games, and by extension any VR application, these are referred to as art assets. As historicity is a major concern for this application, some assets need to be custom-made. The possibly most important amongst them is the 3D model of the sword, representing the tangible in the digital world. It must exactly match the tangible's shape, as well as the historical type XVa longsword it is meant to portray. This is aided by the reuse of the 3D models used in the 3D printing of the tangible, as well as reference material from the *Oakeshott Typology*.

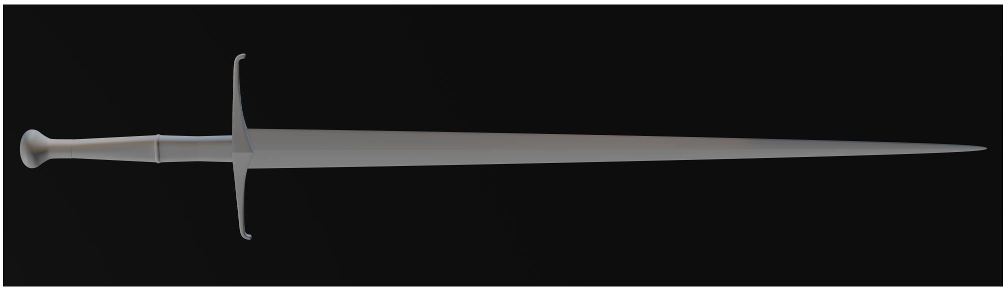


Figure 6.10.: Digital Model of the Used Sword

The other critical art asset, the example character, while created by the author, is not custom-made for this paper. The character, as seen in Figure 6.11, portrays an approximately 15th century man at arms, equipped with a gambeson padded jacket, kettle hat helmet, split hose pants, and leather turnshoes.

Figure 6.11.: The Enemy Character, sourced from author's previous work

Not all assets were custom made for this application. Some are publicly available and freely licensed works by third parties. Table A.1 lays out the origin and license of all the art assets.

7. Evaluation

In order to determine the success of the developed application, it must be analyzed in respect to its stated goals. Of interest are both the historicity of depicted content, as well as its suitability as a training and teaching tool. The historicity is best analyzed by subject matter experts, or by comparing it to the used source material. The accuracy of the tangible specifically can be determined using the mathematical approach described in Subsection 5.3.2. The effectiveness as a training tool is determined through the means of a user study, with corresponding quantitative user data.

7.1. Analysis

7.1.1. Tangible Sword Dynamics

The tangible is built to closely match the dynamics of real swords. To determine the success of the utilized approach, the tangible's physical properties need to be measured and compared to the real sword's dynamics. This measurement process is nearly identical to the one used on the original swords. Complicating factors are the tangible's shortened length and bulky weight near the tip. These make the experiments used to determine the moment of inertia more difficult and less accurate, due to the limited available pivot points. Consequently, the already difficult waggle test did not result in any usable data. The more elaborate pendulum test however worked as expected.

		Theoretical Prototype 4	Measured Prototype 4	Regenyei Talhoffer	Albion Ringeck	Rawlings Synthetic
Mass	(g)	1499	1464	1453	1507	816
COM.	(cm)	6.5	6.2	6.5 - 9	10	18
Inertia	(g/cm^2)	1319.07	1381.73	1329.67	1339.77	608.28
ROG.	(cm)	30.2	25.41	29.55	28.30	30.08

Table 7.1.: A comparison between the dynamics of various swords, including the Prototype and its theorized properties.

The measured values are well within acceptable range for a longsword, but notably different than predicted. The difference in mass and balance point are within the expected margin of error of manual assembly. The moment of inertia and resulting radius of gyration are however, while still acceptable, different enough to hint at a systemic problem in the used tangible design and construction process. One suspected source of this issue is the chosen axis for calculation of the moment of inertia. The design process, like its predecessor in Turner's paper [Tur02], assumes the axis of the given moment of inertia to be in the balance point of the sword. The weapon dynamics computer [Vin] used for the measurements hints at a different axis for its calculations; possibly a point within the hilt. This discrepancy warrants further investigation. The tangible's dynamic properties are however close enough to the reference for the purposes of this paper and its proof-of-concept application.

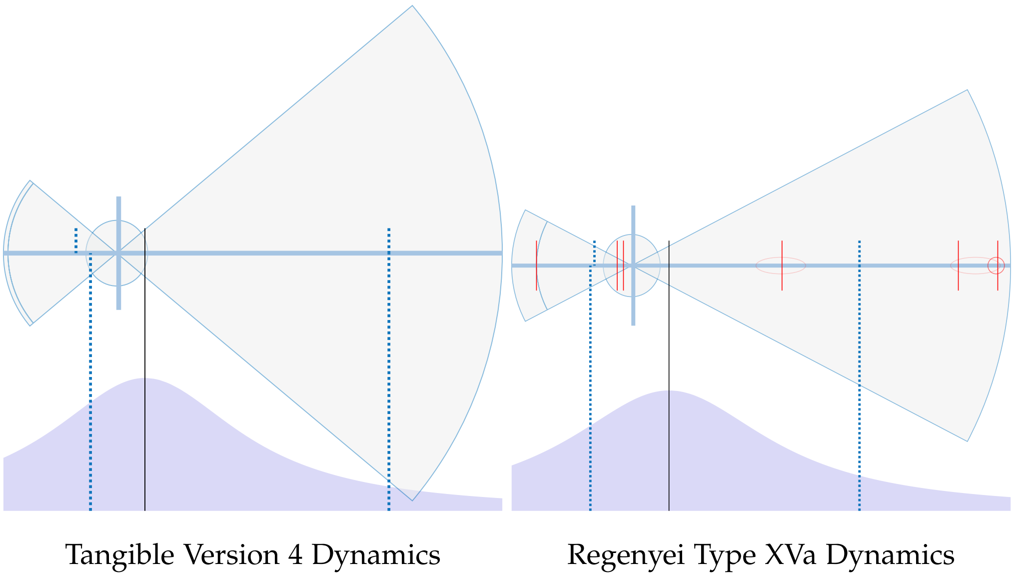


Figure 7.1.: Comparison of the tangible's dynamics to a reproduction longsword.

7.1.2. Application Historicity

The degree of historical accuracy of the content depicted in the application is largely a result of the used source material. The animations showcasing attack techniques in the tutorial level are mostly based on the diagrams in Abart's and Schmidt's work [Aba08] [Sch15]. Their interpretations, while clearly viable techniques, are no longer entirely up-to-date with the current state of research. Artifacts from manual animation, such as stiff movement, further increase the issue. Overall mistakes in animations are only a minor concern, since the affected parts are small details which are not relevant to beginner fencers.

The art assets are overall fairly historical. The enemy character asset depicts a 15th century man at arms with light armaments. While aesthetically similar to period depictions, it is not a direct replica of any museum piece. Therefore some details, such as the sewing pattern of the padded armor do not conform to actual historical reproductions. Overall the asset captures the impression of a late-medieval man at arms, but would need some reworking if used as part of a historical museum demo. The sword asset closely follows Oakeshott's Type XVa longsword pattern, with the exception of the scent-stopper style pommel, which was only popular in the early renaissance, at the time of Meyer. The sword is therefore slightly anachronistic, as a mix of longswords of the 15th and 16th century. The chosen font *Canterbury Regular* resembles some 15th and 16th century texts, including a *Fechtbuch* by Meyer.

The chosen exercises all teach historical skills. The Meyer Square exercise in particular is taken directly from a *Fechtbuch*. The exception to this is the tatami cutting exercise, which is a modern reinterpretation of Japanese swordsmanship. This is however explicitly pointed out in the application. No incorrect information is conveyed. The application as a whole, while not entirely historically correct, gives a good impression of late medieval fencing as interpreted through HEMA.

7.2. User-Study

7.2.1. Method

A user-study was conducted to evaluate the application as a training and teaching tool for HEMA in practice. Most participants of the study were laymen, but some had extensive previous experience. Those deemed subject matter experts were asked to give detailed explanations of their evaluation of the application. In the study participants completed the exercises and then filled out a questionnaire on the perceived usability and their previous experience. Additionally, data on the participants' attempts to master the exercises was gathered and notes on any observed oddities were taken. To determine the benefit of the interactive rework of the Meyer Square exercise, participants were divided into two groups, each playing either the traditional or the interactive version of the exercise.

The study was conducted in the following steps:

1. Introduction on the Topic
2. Data protection Briefing
3. Sword Handling & VR Safety Briefing

4. Equipping of the HMD and Tangible
5. Full Playthrough of the Application
6. Filling out of the Questionnaire
7. Informal Interview, if subject was deemed a subject matter expert
8. Informal chat (optional)

SUS Score

The System Usability Scale (SUS) is a widely used questionnaire for determining a system's perceived usability [Bro95]. It consists of ten questions with answers on a scale from one to five, representing a participant's agreement on given statements. The answers are then evaluated to a single score from 0 to 100. SUS can be used as a quick and easy indication of users' approval of the application. The score can also be correlated with answers from other questions, in order to determine possible issues or strengths in the application.

Experience Score

The purpose of the experience score it to quantify participants' previous experience, both in martial arts, but also with video games. The participants were asked to rate their experience with sports, martial arts, video games and virtual reality. The values are then normalized to a range of $[0, 1]$ and averaged, with two sub-scores for added clarity:

$$S_{Exp} := \frac{S_{Sports} + S_{Digital}}{2}, \quad S_{Sports} := \frac{R_{Athletic} + R_{Martial}}{2}, \qquad S_{Digital} := \frac{R_{Gaming} + R_{VR}}{2}$$

Performance Score

The purpose of the performance score is the quantitative evaluation of a participant's general success and success in the Meyer Square exercise specifically. The goal is to determine learning effect through the gradual improvement of scores.

The performance score is a continuous scale, evaluating the skill and success of participants' during the entire playthrough of the application. It takes into account the quality of the performed strikes as well as the success in the Meyer Square exercise. It is calculated from concrete performance data gathered during the study, including weapon impact speed in m/s, edge alignment error in degrees and the percentage of correctly struck openings in the Meyer Square.

The total performance score is the average of the chopping and Meyer scores.

$$S_{PERF} := \frac{S_{CHOP} + S_{MEYER}}{2}$$

The chopping score is the average of per-strike scores $c_i \in C$.

$$S_{CHOP} := \frac{\sum_{i=0}^{|C|} c_i}{|C|}, \qquad c_i := \frac{s_i + e_i + v_i}{3}$$

with individual factors normalized to $[0, 1]$

- Speed: $s_i := \frac{Speed_i}{20}$
- Edge alignment: $e_i := 1 - \frac{\text{Alignment}_i}{90}$
- Rolling average of strike validity v_i of individual hits h_j:

$$v_i := \frac{\sum_{j=i}^{i+4} h_j}{5}, \qquad h_j := \begin{cases} 1, & \text{if } \textit{Valid Strike}_j = \textit{True} \\ 0, & \text{otherwise} \end{cases}$$

The Meyer score is the percentage of correctly struck openings during the Meyer Square exercise, with individuals strikes $m_i \in M$:

$$S_{MEYER} := \frac{\sum_{i=0}^{|M|} m_i}{|M|}, \qquad m_i := \begin{cases} 1, & \text{if } \textit{Opening Validity}_i = \textit{True} \\ 0, & \text{otherwise} \end{cases}$$

7.2.2. Results

Overall Reception of the Application

Overall the reception, both in given scores and in verbal responses, is exceedingly positive. The subject matter experts, of whom there were four with one notably more experienced than the others, were optimistic. Most participants voiced their enjoyment and reported having fun. The average ratings are also good. The tangible' s perceived authenticity received an average score of 4.6/5, though it was deemed slightly too heavy and nimble. This perception fits the measurements. The three exercises got ratings of 4.2/5, 4.2/5 and 4.4/5 in order of appearance. The interactive version of the *Meyer Square* exercise was rated slightly better than the traditional one, though not to a

	S_{SPORTS}	$S_{DIGITAL}$	S_{EXP}
S_{PERF}	0.20	0.48	0.43
S_{SUS}	0.10	0.62	0.42

Table 7.2.: An analysis of which factors correlate with good performance and perceived usability of the application and to what degree.

statistically significant degree. The SUS average score is 81.5, earning the application a grade of A.

Participants' performance and SUS scores were tested for correlation with their previous experience scores, using the Pearson correlation coefficient [NA24a]. Previous athletic experience coincided with a slightly better performance, but only a negligible improvement in SUS score. Experience with gaming and VR however, strongly correlates with better performance and much better perceived usability. This suggests that any usability issues are related to unfamiliarity with gaming specific interaction methods, such as the concept of a level-select menu.

A few issues commonly arose. Many participants reported difficulty in reading the font, leading to worse understanding of the given instructions. From observations a participant's thoroughness in reading them seems related to improved performance. Rare issues were encountered at the extremes of the skill spectrum. A single contestant moved faster than the application was able to reliably track. A few contestants with little to no martial or athletic background struggled to follow the instructions given by the application, as they lacked awareness and control of their own body. Typically, this is greatly alleviated once the example characters are shown not only opposite, but also next to the test subjects. Overall the application successfully showcased historical techniques, particularly for users who did not struggle with hand-eye coordination. In general there was a large disparity in ease of learning between different test subjects. Difficulty settings were requested multiple times. However many participants who initially faced difficulty reported a moment of sudden realization, after which they performed much better.

Evaluation of Learning Progression

In order to quantify the effectiveness of the teaching method, participants' cutting scores are tracked throughout their entire playthrough. This data is very noisy and thus offers little direct insight on a per-user basis. Averaging the scores of every player smooths the resulting graph, allowing some analysis. Since a few players played significantly longer than others, the end of the graph, where only a quarter of the participants are still active, has much lower statistical significance with a rising level of noise. The dip at the end can therefore be ignored, as it is the result of a single participant's fluctuating performance. Overall there is a clear upwards trend in participants' performance. The average score almost doubles, from ca. 0.35 to 0.7, within the section of the graph of statistical significance.

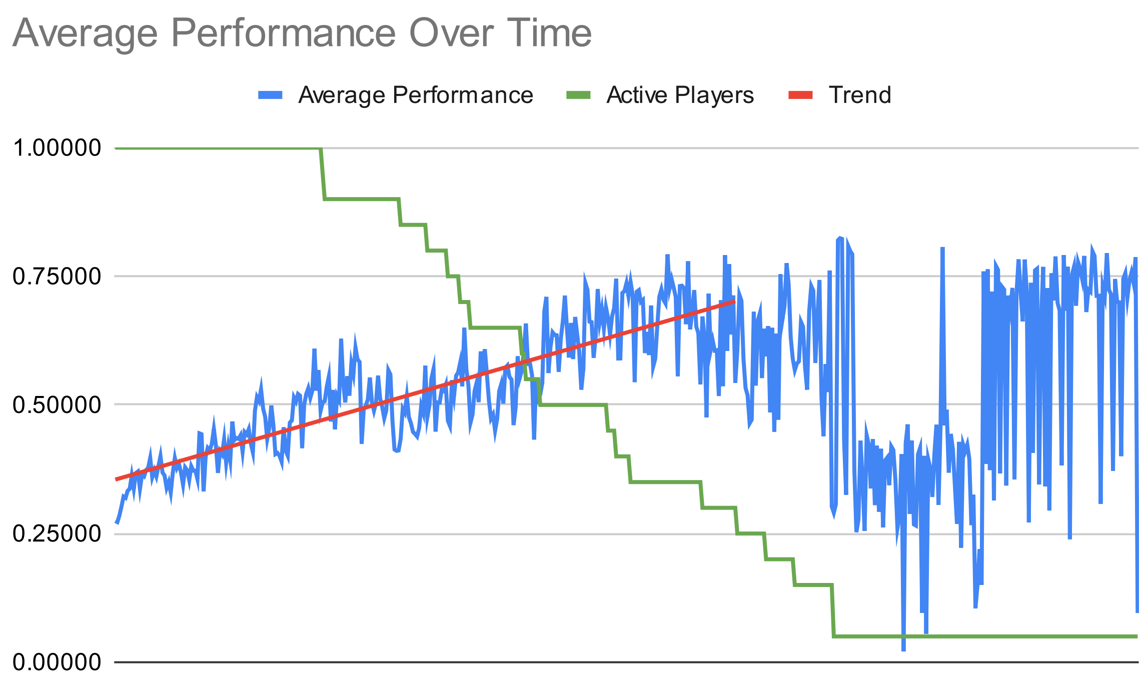


Figure 7.2.: Average cutting performance score c_i of all participants over time showing a clear upwards trend within the statistically significant section

It is safe to say, the test subjects learned to wield swords much better than they could before. This data fits the self reported effect of learning, with an average score of 4/5 for the statement *"I learned a lot about historical fencing."*. Furthermore the application's viability as a tool for regular practice was rated 4.37/5.

Added Value of Virtual Reality

VR provides an interactive and immersive experience very different from conventional solo-practice. This is an advantage in creating interest and holding people's attention by providing a playful learning environment, with most study participants reporting having fun and many even giggling during their playthrough. The immersive three-dimensional experience proved particularly useful in the attack technique introduction. Multiple test subjects walked around the play area in order to view the example characters from different viewpoints to better understand the intended stance. Some participants profited from seeing the characters perform the techniques in motion, after having difficulty understanding them from the still depictions.

The second exercise, the tatami cutting practice, also benefits from the advantages of VR. The main interviewed subject matter expert, who has a decade of HEMA experience, praised the opportunity to easily train proper edge alignment. He remarked on the significant overhead, both practical and financial, of cutting practice in real life. He imagines the application as useful for beginner fencers as a solo-training tool, if participation in a fencing school is not yet an option.

The added value of interactivity to the Meyer Square exercise can be determined by data-driven analysis, by comparison of the given scores of both tested groups in the user-study. The SUS score, as well as the rating given to the Meyer Square exercise and the performance scores all improved in the interactive version of the exercise, when compared to the traditional one. Most of these results are however not statistically significant, with the U-value, as determined by the *Mann-Whitney U-Test* [MW47] [NAndf], being much larger than the target of 20. It is therefore inconclusive, if the interactive version is actually perceived as more usable or fun. The participants' performance S_{MEYER} in the exercise improved however significantly by 17%. This data fits with the observations of test subjects quickly performing the interactive exercise with little difficulty, but having to contemplate their next move in the traditional version. This is especially important, as the Meyer Square exercise is meant to train the fast chaining of cuts and mental hurdles hinder this goal.

Exercise	SUS Score	Meyer Rating	S_{MEYER}	S_{PERF}
Total	81.15	0.86	0.91	0.70
Traditional	80.36	0.81	0.84	0.68
Interactive	82.08	0.90	0.98	0.72
Improvement	1.73	0.09	0.14	0.04
Relative Imp.	2.15%	11.72%	16.62%	5.81%
U-Value	30.5	36.0	3.5	34.5

Table 7.3.: A comparison between the traditional and interactive versions of the Meyer Square exercise in relation to player performance and usability score.

8. Conclusion

To demonstrate the viability of the utilization of VR as a training and teaching tool for historical fencing (HEMA), a proof-of-concept application, consisting of three exercises, was developed and a tangible representing a longsword was constructed.

The tangible was designed to mimic the handling of steel training longswords. Its shape is based on historical 15th century longswords, categorized as type XVa in the *Oakeshott Typology*. Different methods of construction were attempted, eventually settling on a 3D-printed hull of interlocking parts around a threaded rod. This method enables rapid iteration using modular and light-weight parts, whilst resulting in a structurally strong tangible. The design process takes into account the tangible's dynamic properties such as mass, balance point and the moment of inertia. The resulting measurements are close to the intended target, but do not match entirely. The deviation from the theorized moment of inertia should be explored further. Despite this minor difference to the historical reference, the user-study, including four subject matter experts, rated the tangible positively, proving its viability for the purposes of virtual fencing.

The application consists of three exercises, chosen to build on each other, whilst taking into account the limitation of lack of full-body tracking and force feedback. The first exercise used custom-made animations to introduce users to fundamental concepts of HEMA and teach basic attack techniques. The second exercise deepened the user's understanding of correct striking techniques. The third exercise improved on a historical flow-drill in order to train the user's muscle memory and give an outlook on more complex compound-techniques. Special attention was paid to considerations of usability and the added value of VR.

In a study, the achieved learning effect was measured, with the average user almost doubling their performance score over the course of a playthrough. The added value of VR, was praised by the leading subject matter expert of the study. For the third exercise, where A/B testing was employed, participants making full use of the interactivity of VR performed 17% better than those taught using traditional teaching techniques. A comparison of the SUS score remained inconclusive.

Overall the proof-of-concept is deemed a success. VR proves suitable to the training of HEMA with clear improvements over regular training. The achieved learning effect as well as user reception is very positive.

9. Future Work

Some minor issues were uncovered. The difference between the predicted and measured moment of inertia of the tangible, although within historical limits, should be investigated further. Some of the results from the evaluation are inconclusive. They might benefit from a repeated study with a larger pool of participants, as well as more data gathered by the application itself, allowing for a more precise interpretation.

However, given the overall very positive results of the proof-of-concept, a long-term project improving on the developed application might be viable. The steps to this are described in Chapter 2. The next step should likely be the incorporation of full-body tracking for improved technique evaluation or the fully physical simulation of the sword in the virtual world, allowing for blade-on-blade contact.

A. General Addenda

A.1. User Study Questionnaire

Introductory Text
This questionnaire is part of a study conducted to evaluate the utilization of virtual reality games as a training and educational tool on the topic of historical fencing. The tested prototype consists of three exercises. The game stores data on your performance in order to evaluate the learning effect. All data, both of the game and the questionnaire, is stored anonymized. It cannot be traced back to individual persons. Optionally you may volunteer to be filmed during the study. This video will not be published.

Organizational Information

1. Session ID-Code (Ask Organizer) *[Text Field]*
2. Which version of the Meyer Square exercise did you do? (Ask Organizer)
   Interactive | Traditional

Demographic Information

1. How old are you?
2. What gender are you?

Previous Experience

1. Rate your own knowledge of medieval history
   Low - 1 | 2 | 3 | 4 | 5 - High
2. Rate your interest in medieval history
   Not interested - 1 | 2 | 3 | 4 | 5 - Very Interested
3. Please rate your previous knowledge of swords
   None - 1 | 2 | 3 | 4 | 5 - Expert
4. Have you handled real swords before?
   Never | Occasionally | Sometimes | Often
5. Rate your general athletic ability
   Unfit - 1 | 2 | 3 | 4 | 5 - Very Fit
6. Have you ever practiced martial arts?
   Yes | No

Details Martial Arts Experience ***[Optional]***
1. Which type of martial art have you practiced?
2. For how long have you practiced martial arts?
3. Please rate your skill level
   Unskilled - 1 | 2 | 3 | 4 | 5 - Very Skilled

Gaming Experience
1. How often do you play video games?
   Never | Occasionally | Sometimes | Often
2. Have you used Virtual Reality before?
   Never | Occasionally | Sometimes | Often

Prototype Evaluation
The following questions are to be answered after the prototype has been tested.

Prototype Evaluation - Sword
1. The sword feels real.
   Strongly Disagree - 1 | 2 | 3 | 4 | 5 - Strongly Agree
2. The sword's shape fells authentic.
   Strongly Disagree - 1 | 2 | 3 | 4 | 5 - Strongly Agree

Attention
In the following questions, "3" represents the optimum, not "5". The scale here is not from left to right, but from the center out.

3. The sword's weight is
   Too light - 1 | 2 | 3 | 4 | 5 - Too heavy
4. The sword's balance is
   Too nimble - 1 | 2 | 3 | 4 | 5 - Too heavy
5. Feel free to comment on the sword (Optional) *[Text Field]*

Prototype Evaluation - Exercises
1. Please rate the cutting introduction
   Very Bad - 1 | 2 | 3 | 4 | 5 - Very Good
2. Feel free to comment on the cutting introduction*[Text Field]*
3. Please rate the tatami cutting practice
   Very Bad - 1 | 2 | 3 | 4 | 5 - Very Good
4. Feel free to comment on the tatami cutting exercise*[Text Field]*
5. Please rate the Meyer Square flow drill
   Very Bad - 1 | 2 | 3 | 4 | 5 - Very Good

6. Feel free to comment on the Meyer Square flow drill*[Text Field]*

Prototype Evaluation - Usability

This section consists of the 10 questions of the SUS questionnaire.
2. Feel free to comment on the Usability. (Optional) *[Text Field]*

Prototype Evaluation - Learning

1. The game sparked my interest in historical fencing.
   Strongly Disagree - 1 | 2 | 3 | 4 | 5 - Strongly Agree
2. The game gave me a good impression of historical fencing.
   Strongly Disagree - 1 | 2 | 3 | 4 | 5 - Strongly Agree
3. I learned a lot about historical fencing.
   Strongly Disagree - 1 | 2 | 3 | 4 | 5 - Strongly Agree
4. The game could help me with regular fencing practice.
   Strongly Disagree - 1 | 2 | 3 | 4 | 5 - Strongly Agree
5. Feel free to comment on the learning effect. (Optional) *[Text Field]*

A.2. List of Art Assets

Asset	Origin	License
Models		
Character	Jonas Hack	
Longsword	Jonas Hack	
Animations	Jonas Hack	
Meyer Square	Jonas Hack	
Textures		
Tatami Inside	Jonas Hack	
Bamboo Wall	cc0-textures.com	Public Domain
Fabric (22)	cc0-textures.com	Public Domain
Metal (12)	cc0-textures.com	Public Domain
Paper (6)	cc0-textures.com	Public Domain
Wood (62)	cc0-textures.com	Public Domain
Grass (3)	cc0-textures.com	Public Domain
Grass Path (2)	cc0-textures.com	Public Domain
Brown Mud	cc0-textures.com	Public Domain
Lilienstein HDRI	polyhaven.com	Creative-Commons-0
Illustrations		
Talhoffer Longsword	wiktenauer.com digitale-sammlungen.de	CC-BY-NC-AS
Meyer Square	wiktenauer.com digital.ub.uni-leipzig.de	Public Domain
Audio		
Sword Sound	freesound.org	Creative-Commons-0
Sword Clash	freesound.org	Creative-Commons-0
Hit Wood	freesound.org	Creative-Commons-0
Fonts		
Canterbury	1001fonts.com	1001Fonts FFC
Goudy Initialen	www.1001fonts.com	1001Fonts FFC

Table A.1.: List of all Used Art Assets

Abbreviations

HEMA Historical European Martial Arts

VR Virtual Reality

SUS System Usability Scale

HMD Head Mounted Display

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