MASTER THESIS

INTELLIGENCE AND MOTION

A BIOMECHANICAL ANALYSIS OF TECHNIQUE TRAINING AND FREEFIGHT IN HISTORICAL EUROPEAN MARTIAL ARTS

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Sei aufgelegt zu Lust und Scherz, Fechten verlangt Herz

— HANS TALHOFFER

ABSTRACT

In this empirical thesis Longsword techniques from the Historical European Martial Arts (HEMA) were examined in training and freefight. The aim of this thesis is to examine the difference of a technique in training and freefight. German Longsword sources from Liechtenauer et al. (1504-1519) and Juden et al. (around 1400) were examined. Six Guards, seven Principles and 14 Master strike variations were measured. To collect the data an inertial measurement system was used in training and freefight situations. Nine HEMA fighters were equipped with 16 acceleration sensors to measure the movements in training and freefight. For the experiment the subjects filled in a questionnaire and participated in two experimental parts. The first part consists of a Longsword training and the second of a combat performance. In the post-processing the techniques were annotated manually by a HEMA expert. The techniques have significant different biomechanics in freefight and training for Guards, Principles and Strikes. The shortest technique duration were less than 1.40 s during training. An average fight takes 24.96 s. *Cross strike - attack the openings* is the technique with the fastest sword-point velocity of 14.09 $\frac{m}{s}$.

ACKNOWLEDGEMENT

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Heike Merkert

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TRANSLATIONS

English	German
after strike	Nachschlag
attacking after	Nachreisen
barrier guard	Schrankhut
be on the watch	auf der Hut sein
be up for desire and joke, fencing demands heart	Sei aufgelegt zu Lust und Scherz, Fechten verlangt Herz
binding	Bindung
block	versetzen
change	see mutating
changing through	Durchwechseln
crooked strike	Krumphau
cross	Parierstange
cross guard	see hilt
cross strike / zwerchau	Twerhau
crown	Kron
cut	Schnitt
displacement	see setting off
double	see doubling
doubling / double	Duplieren
false edge	kurze Schneide
feel	fühlen
first strike	Vorschlag
following-after	Nachreisen
fool	Alber
from the roof	Vom Tag
gate	Pforte
guard / ward / leger	Hut
hanging	Hengen
hanging point	Hängetort
hilt / cross guard	Gehilst
in the Instant	indes
key	Schlüssel
leger	see guard
long point	Langort
longsword	Langes Schwert
lower hanging	Undenhengen
master strike	Meisterhau
mutating / change	Mutieren
opening	Blöße

English	German
ordeal by battle	Gottesurteil durch Zweikampf
Overrunning	Überlaufen
ox	Ochs
parting strike	see scalp strike
Pass Through	Durchlaufen
plough	Pflug
point	Ort
pommel	Pommel
principles	Prinzipien
rage guard	Zornhut
rage strike / wrath strike	Zornhau
rebounding / taking off	Abnehmen
scalp strike / parting strike	Scheitelhau
setting off / displacement	Absetzen
side guard	Nebenhut
Snapping Around	Umschnappen
speaking window	Sprechfenster
squinting strike	Schielhau
stitch	Stich
strike	Hau
strong	hart
strong	Stärke
taking off	Abnehmen
thumb grip	Daumengriff
true edge	lange Schneide
turning	see winde
twitching / withdrawing	Zucken
unarmored longsword combat	Blosfechten
unicorn	Einhorn
Unterhau	Unterhau
upper strike	Oberhau
ward	see guard
weak	Schwäche / weich
winde / turning	winden
withdrawing	see twitching
wrath strike	see rage strike
wrath thrust	Zornhau Ort
zwerchau	see cross strike

ABBREVIATIONS

Abbreviation	Description
B	Boxing
C	Count
cor	Correlation
C7	Cervical segment 7
DF	Degrees of Freedom
DTW	Dynamic Time Warping
EMG	Electromyography
GS	Group size
HEMA	Historical European Martial Arts
IBRM	Infraredbased retroreflective markers
Ka	Karate
Ke	Kendo
KF	Kung-Fu
MP	Movement Primitive
MPHR	Maximum predicted hit rate
MV	Maximal velocity
R	Repetitions
S-D	Self-Defense
SD / sd	Standard Deviation
Sig	Significant
SPV	Swordpoint velocity
S2	Sacrum 2
TC	Tai Chi
T10	Thoracic vertebra 10
WMA	Western Martial Arts

1 INTRODUCTION

This thesis investigates Historical European Martial Arts (HEMA) Longsword techniques biomechanically in training and freefight situations.

In HEMA, there exist mainly two different opinions on how to fight in a freefight and how to prepare for freefights. One group trys to study the sources and copy the movements as accurately as possible in training and freefight. The other group of fencers has the opinion that the sources are nice but not useful and usable in a freefight situation[1]. With this experiment the difference of a technique in training and freefight is examined. This thesis provides an answer based on qualitative data which could put an end to this debate.

Historical European Martial Arts (also known as European Martial Arts or HEMA) are fighting techniques which were common in the areas of European from the 13th to the 17th century. Trained techniques were written down in fencing manuscripts during the Middle Ages and the Early Modern Era. The manuscripts describe complex techniques for nearly every situation and different weapons.

One of the most famous fencing books is Talhoffers Fechtbuch (Talhoffer, 1467) which includes 137 pages and a description, plotted and written by Hans Talhoffer (see Figure 1.1). But he was not the only one who wrote down techniques for training, many more described and portrayed techniques for various weapons.

The interpretation of the ancient sources is a huge task on which many clubs are working. This work is necessary because of the broken tradition of HEMA after the Late Middle Ages. On the other hand take the example of Karate. It was trained continuously and every technique was passed on from the master to the student over several hundreds of years. Because of the need for interpretation in HEMA, there is often more then one interpretation for a technique dependent on the interpreters and

1 a not choreographed battle between two or more fighters, which are protected and have unsharp weapons

(a) Longsword technique page 2v.

(b) Poleaxe technique page 46v.

Figure 1.1: Drawing and text of techniques from Talhoffers Fechtbuch (Wiktenauer).

their knowledge of other Martial Arts than HEMA. This also heats up the discussions.

A lot of literature has been published dealing with the technical interpretation, comparison of fight books, transcription, translation and edition of source material, research on the original and research of knowledge transmission. Only a few articles exist about investigations in combat movements and physiology of historical techniques.

Jaquet (2016a) evaluated historical sources of the so-called Strike *flügel* and compared two different versions of it using objective and subjective criteria. Jaquet used a protocol and video footage for the evaluation.

In preparation for this thesis an experiment was done by using augmented reality glasses during HEMA training by Merkert & Möller (2017). The goal was to improve the performance and to control the speed of the technique. This was done by showing technique videos before or during the technique performance.

Another prestudy for this thesis was about the heart rate variability in HEMA freefight performed by Merkert (2018). The heart rate and the variability was measured to get the stress levels of the fencers during the freefight.

Farlock (2018) made an eye tracking study with expert and novice HEMA fighters and HEMA unexperienced people. The main object was the difference of the perception at different experience levels.

The lack of experimental studies in the third field in HEMA

may be based on the definition of HEMA research. As Jaquet (2016b) found out, 65 % of the HEMA community thinks that the main goal of the research in this field is the training itself and working on the sources, which could be search, transcribe and translate the source. Around one fourth defines HEMA research like all other forms of applied research, where sources need to be found, the environment needs to be controlled, hypotheses need to be set and tested and the results have to be analysed and evaluated. 2.5 % of the HEMA community disapprove of practical tests in HEMA at all (Jaquet, 2016b).

In the following the method to test one specific Martial Art (Price, 2006) is taken into account. This thesis examines HEMA. In two settings (training and freefight) the biomechanics of Longsword techniques were measured. For this, experienced fencers were tested.

This thesis pushes the experimental research of HEMA, because it takes a closer look at the swordpoint velocity during different techniques and the biomechanics of the Longsword techniques. To do so a biomechanical analysis of six guards and 21 techniques with the Longsword during training (part I) as well as a biomechanical measurement during 32 freefights (part II) per person was examined.

This master thesis can can help better understand the historical sources in HEMA. Training and freefight situations were measured and compared with each other. This could help fencers to train more effectively for sparring situations and to improve their fighting skills.

In Chapter 2 Historical European Martial Arts is introduced. The differences between Guards and Strikes are described and freefights are explained. Related works are presented and the hypotheses are defined.

In Chapter 3 the used equipement is specified. The experimental preparation, setup and procedure is described. At last the steps of the post-processing are specified.

The results are described in Chapter 4. The characteristics of the participants are depicted. The technique count and the technique recognition rate in freefight is specified. The results of the movement comparison between training and freefight are summarised. The duration of the techniques and the freefights

and the swordpoint velocity are mentioned.

In Chapter 5 the results of 4 are discussed. The conclusion and possible future work is summarised in Chapter 6.

The appendix includes additional tables (Chapter B), descriptions of the measured Guards (Chapter C), Principles (Chapter D) and Master strikes (Chapter E) and the used questionnaire (Chapter F).

2 BACKGROUND INFORMATION

Previously, a short perspective of this thesis was listed. In this chapter a short overview of European Martial Arts is given. It is not complete in any way but has the purpose to give all HEMA newcomers a peek into the matter to understand this thesis. To do so the following questions can be asked: What is HEMA? Which weapons were used in the Middle Ages and which of them were examined in this thesis? What are Wards, Principles and Master Strikes and which of them are examined? What does a freefight mean? Why making a biomechanical analysis?

2.1 HISTORICAL EUROPEAN MARTIAL ART

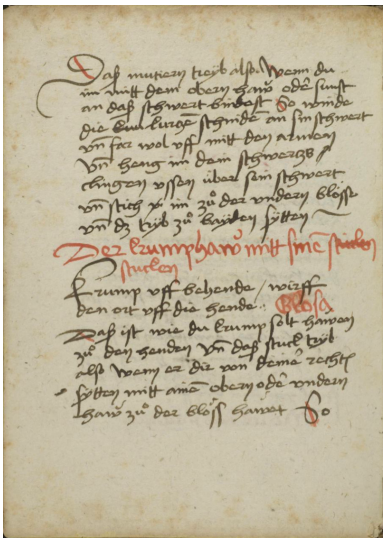
HEMA is an abbreviation for Historical European Martial Arts, also known as European Martial Arts or Western Martial Arts (WMA).

Historical

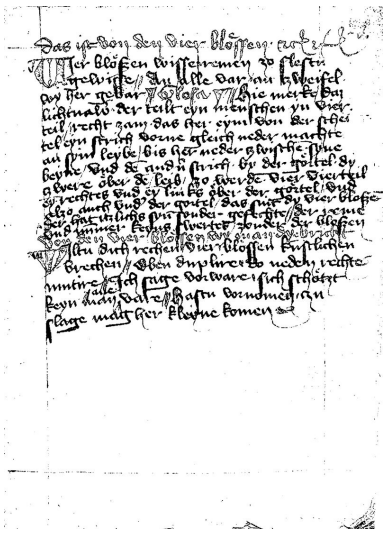
The term *historical* pictures the fact that all sources are from the 13th to the 17th century. The term is often left out because most of the martial arts have historical backgrounds. Early forms

(a) Source text. (b) Drawing.

Figure 2.1: Longsword Principle Mutating from Falkner et al. (1510-1520) 17r and 17v.



(a) Liechtenauer et al. (1504-1519) page 24v.



(b) Juden et al. (around 1400) page 25r.

Figure 2.2: Historical source texts for the Longsword Principle Mutating.

of Karate have existed since 794 (Green, 2001). The same applies to many other martial arts.

All known HEMA sources are text and/or drawings. An example for a HEMA text source in combination with a drawing from Falkner et al. (1510-1520) is shown in Figure 2.1. The text of it is written in Early New High German, the language of the medieval times[1] from the northwest of Switzerland to Central Germany. The date of most of the sources is estimated and may not be correct. Some sources have the publishing date written in the book. The other sources are estimated palaeographycally[2]. An example of the sources for the Longsword Principle Mutating from Liechtenauer et al. (1504-1519) is shown in Figure 2.2a and from Juden et al. (around 1400) in Figure 2.2b. In this thesis only sources from Liechtenauer et al. (1504-1519) and Juden et al. (around 1400) were used because they summarise the main Longsword techniques.

European

European Martial Arts stands in constrast to Asian Martial Arts. Typical European Martial Arts besides fencing are, Savate (France), Boxing (Greece) and Wrestling (Greece, Russia) (Tausk

1 1350-1650 (Early New High German; 2019)
2 study of historical handwriting

& Clements, 2001). For medieval fencing, sources exist from all over Europe. They are from Spain (Greatsword from unknown, 1563), Portugal (Greatsword from de Figueyredo, 1651), France (Poleaxe from unknown, 1400), Italy (Longsword from di Vadi, 1482-1487) and Germany (von Danzig zum Ingolstadt et al., 1452; Falkner et al., 1510-1520). Liechtenauer et al. (1504-1519) and Juden et al. (around 1400), which are used in this thesis are German sources.

Martial arts

Martial arts is the training and study of armed and unarmed fighting skills. Wetzler (2014) divided Martial Arts into five dimensions. The sports dimension, the dimension of the exercise of violence, the dimension of performance, the dimension of philosophy and the dimension of healthy body exercise. Bodemer (2008) described the art of fencing as a sportive combat between two people.

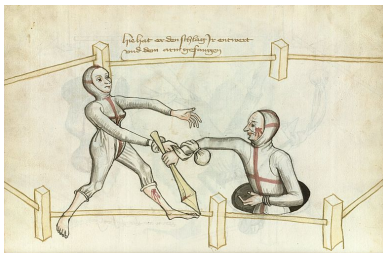
Clements (2006b) defines Martial Arts in the Middle Ages as the 'arts of Mars[3]'. Clements wrote that in the 1550s the term 'Martial Art' was already used in Europe. Later on 'fencing' and 'Martial Arts' seem to be similar. As Clements said, fencing was the exercise of arms.

The art was taught in fencing schools in the Middle Ages. At these schools fencing masters like Tallhofer and others wrote down and taught the art of fencing (Haage & Wegner, 2017; Bodemer, 2017). The techniques learned were also demonstrated in public performances. In training and shows no one was harmed seriously. Fencing was not only to entertain people and to spread the good reputation of the school, it was also a deadly art. HEMA was used in battles, in ordeal by battle and from bodyguards for personal security.

The sources which will be taken into account in here are for ordeal by battle (Israel, 2017). This kind of duel was held, when two parties could not come to an agreement. Those were battles of life and death. When one could afford a fencer, he could pay one to fight the combat for him. If not, he needed to fight for himself. It was also possible that a man fought against a woman. For that the man was put into a waist-deep hole and one hand was strapped to the front (see Figure 2.3a). In Figure 2.3b, a historical source with equal fighting conditions between man

3 Roman god of war

and woman is pictured. One can assume, that these pictures show a rare exception and women normally did not learn the art of fencing.



(a) Ordeal by battle man vs woman from Talhoffer Fechtbuch 80v.

(b) Sword & Buckler from MS I.33 31r.

Figure 2.3: Fighting women.

Weapons

As seen above, different weapons were used in HEMA. From Wrestling[4] to Dagger[5], Long Knife[6] and Longsword[7] to Greatsword[8] and Poleaxe[9]. Those weapons are shown in Figure 2.4. Some more weapons exist from the Middle Ages like Long Pole, Lance, Halberd and so on (Ortenburg, 1984; Hagedorn, 2017; Fiedler, 2017; von Danzig zum Ingolstadt et al., 1452; Falkner et al., 1510-1520; Liechtenauer et al., 1504-1519).

The weapon which is examined in this thesis is the Longsword. It is a weapon which is wielded in two hands. The Longsword is around 110 cm to 140 cm long and has a weight of about 1.2 kg to 1.8 kg. When used in training and in freefight situations none of the weapons is sharp or very spiky. This thesis investigates Longsword techniques.

4 Wilkens, 2017); von Danzig zum Ingolstadt et al., 1452; Liechtenauer et al., 1504-1519

5 von Danzig zum Ingolstadt et al., 1452; Falkner et al., 1510-1520; Juden et al. around 1400

6 Fiedler, 2017; von Danzig zum Ingolstadt et al., 1452; Falkner et al., 1510-1520; Liechtenauer et al., 1504-1519; Juden et al. around 1400

7 Wanke, 2009; Fiedler, 2017; di Vadi, 1482-1487; von Danzig zum Ingolstadt et al., 1452; Falkner et al., 1510-1520; Liechtenauer et al., 1504-1519; Juden et al. around 1400

8 Wanke, 2009; Fiedler, 2017; unknown, 1563; de Figueyredo, 1651

9 unknown, 1400; Falkner et al., 1510-1520

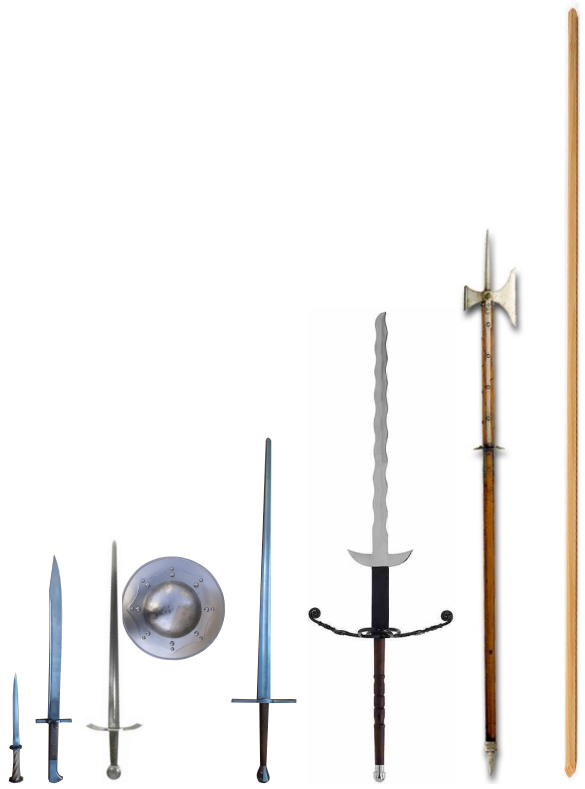


Figure 2.4: HEMA weapons in relation to each other; f.l.t.r.: Dagger, Long Knife, Sword & Buckler, Longsword, Greatsword, Poleaxe, Half Pole.

2.2 TECHNIQUES

In the Late Middle Ages fencing masters had developed many different techniques in Longsword fighting (Leiske, 2018). Those techniques are divided into Guards and Strikes. The Strikes can be graduated into Principles and Master Strikes.

Guard

Ward, Guard or Leger is a basic position in medieval fencing. In early fencing sources four guards are described: *Ox*, *Plough*, *Fool* and *From the Roof* (von Danzig zum Ingolstadt et al., 1452). The concept of guards is related to the saying 'be on the watch'. The sources say, that one should not perform any other than these four guards (Liechtenauer et al., 1504-1519). In later sources the wards *Side guard* and *Barrier guard* are named (Juden et al., around 1400; Liechtenauer et al., 1504-1519; Falkner et al., 1510-1520). Falkner et al. (1510-1520) also described the *Speaking Window* and *Long Point*. More guards are described by Meyer

(1560).

For this study only six Guards were measured. *Ox*, *Plough*, *Fool*, *From the Roof*, *Side guard* and *Barrier guard* were analysed because they are named in the early sources. Wards named later are similar to the ones chosen or do not threaten the opponent which does not seem useful in a freefight. All measured Guards can be seen in the appendix (see Chapter C).

Strike

Of every Guard it is possible to attack or to parry. There are three ways to injure the opponent. The Strike, the Stitch and the Cut. As seen in Figure 2.5, a Strike can be performed from top downwards (Upper strike) or from the bottom upwards (Unterhau). To perform a Strike, the sword is guided along a straight line without an impulse forward or backward.

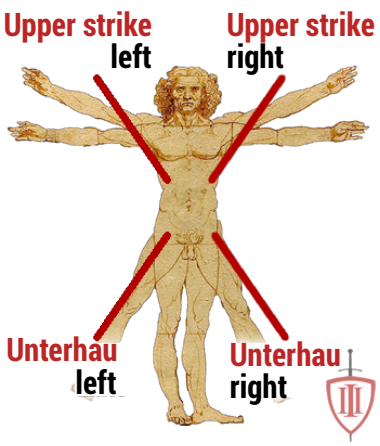


Figure 2.5: Examples for Strike directions (Drey Wunder Codex).

For a Stitch, the tip of the sword (Point) is held toward the opponent and brought directly to him. In unarmored Longsword one can aim everywhere to hurt the opponent.

The Cut is similar to the Strike. The main difference is that one pushes or pulls the sword in the instant when the blade touches the opponent.

Principles

Liechtenauer et al. (1504-1519) wrote down some Principles for fencing which could and should be used in a fight. These Principles are some simple rules to get control over a particular situation in a freefight. Other Principles are more complex and include different graduations of more complex fighting sit-

uations. A closer look was put on fourteen Principles. Seven of them were used in this study because of their usability in Longsword freefights.

Principles used in this study were *Taking Off*, *Setting Off*, *Doubling*, *Changing through*, *Mutating*, *Following-After* and *Twitching*. All these Principles are described in Juden et al. (around 1400) and / or in Liechtenauer et al. (1504-1519). In collaboration with freefight experts the examination of these Principles was recommended, even though not all Principles were researched. Principles not investigated are *Slicing Off* and *Pressing the Hands*, the *Error*, *Pass Through*, *Crown*, *Snapping Around*, *Turning* and *Overrunning*. The description and sources of all Principles used can be seen in the appendix, Chapter D. Videos of the Principles are on the additional disc.

Master Strikes

Apart from the Principles, so called Master Strikes or Secret Strikes were described in sources from the Late Middle Ages. Secret Strikes can be done to parry the opponent's attack and injure him at the same time. They include the *Rage strike*, the *Crooked strike*, the *Squinting strike*, the *Scalp strike* and the *Cross strike*. Each of these strikes breaks a Ward. The *Crooked strike* breaks the Guard *Ox*. The *Cross strike* breaks the Ward *From the Roof*. The third Master Strike, the *Squinting strike* breaks the *Plough*. The *Scalp strike* breaks the Ward *Fool*.

Every Secret strike can be performed in different situations. For the *Crooked strike*, the *Cross strike* and the *Range strike*, four variations are explained in the sources. For the *Scalp strike* and the *Squinting strike* three situations were spelled out. In total there are eighteen variations. For the study only fourteen of these situations were measured. Four of the settings were not included in the measurement because they are similar to others. The description and sources of the measured Master Strikes can be seen in the appendix, Chapter E. Technique videos of the Master Strikes are on a seperate disc.

2.3 FREEFIGHT

A freefight is a combat between two people who have not arranged the techniques they perform. So none of the fight-

ers knows the technique the opponent uses to attack or parry. Nonetheless, there are some rules the fencers need to follow.

Equipment

To protect oneself in training and in the freefight all fencers wear protective gear. It consists of a fencing helmet (1) which bears up to 1600 Newton. Because it is not forbidden to attack the back of the head an extended protection of the back of the head (1) is also necessary. A throat protection (2) is essential to protect the throat especially from stitches. Also important are good gloves (3), because the hands are, after the head, one of the main aims in the freefight. To protect the torso fencers wear a fencing jacket (4). Additionaly one can wear a groin guard, to protect the manhood. Some fencers wear protection for the chest, the forearm and the shinbone (5). An example of the protective gear can be seen in Figure 2.6.

In Longsword freefights every fencer has a Longsword. The sword can be made from different materials - plastic, wood or steel. For this study Longswords made of steel were used. The weapons were not sharp and to reduce the danger from thrusts a small rubber safety tip was put on the point.

Fighting rules

In HEMA many systems of rules exist. Some describe counting points for every hit, others focus on surviving a fight. In this study the rules of HALAG·3W (Lümkemann & Gyarmati, 2017) applied. These rules originate from the HALAG rules (Hampel

Figure 2.6: Example of protective gear for HEMA freefight (1) helmet and extended protection for the back of the head (2) throat protection (3) gloves (4) fencing jacket (5) shinbone protection.

& Wenzel, 2015). The HALAG·3W is described as follows.

The fencers start from the large fighting distance. This distance differs for every weapon. In general the fighters stand far enough away so they can not reach each other with the weapon by making one step forward. They are not too far away to need to walk more than four steps to attack the opponent. In tournaments the fighting area is limited to around 8x8 meters.

The fight ends when at least one of the fencers receives a lethal hit or two non-lethal hits. Lethal hits are strokes and thrusts to the chest, head or neck. Non-lethal hits are not properly defined. Gentle contact and pats can be ignored and do not count as hits.

After a hit a last counter-attack of the one who got 'killed' is permitted. This attack needs to be within one second after the last hit. This often happens, when the attacker does not leave the weapon distance after his strike.

Every fighter counts the strikes he gets for himself. One does not count the strikes of the opponent. If the fighters do not agree on the outcome of the fight, an observer can be asked, if one is present.

Lümkemann & Gyarmati developed a system to collect the data from every fight. This system called CHALLENGE·3W was used in this study. It is a system which collects the outcome of every fight by scanning QR-codes (Gyarmati, 2016). Every fencer gets three QR-codes. One code for the case he did not get injured, one code if the fencer got one non-lethal hit and one code if he got one lethal hit or at least two non-lethal hits. At the end of a fight the fencers scan their survival status.

2.4 RELATED WORK

In Martial Arts sports science studies strive to improve the skills of the fighter and trainer (Lüdemann et al., 2014). To get better in Martial Arts Bussweiler et al. (2011) wrote that elements of technique[10] and tactics[11] are examined. Bussweiler et al. (2011)

10 Fuchs et al., 2015; Endler, 2015; Witte et al., 2010; Hofmann & Witte, 2011; Hofmann et al., 2008; Miyawaki et al., 2012; Koshida et al., 2011; Cabral et al., 2010; Kunze et al., 2006

11 Lüdemann et al., 2012; Staller & Racky, 2014

also mentioned that performance diagnostics are made and new technologies to improve the analysis in competition and performance diagnostics, are developed.

There are also studies which control the trainer performance (Richartz, 2014) or examine the reasons for the fascination of Martial Arts (Kuhn & Macht, 2014). Martial Arts as recovery (Burschka & Kuhn, 2013) and for self-development (Liebl et al., 2016) are also research fields. Further experimental variables in Martial Arts are reaction time, speed, power and others (Fernandes et al., 2011).

Methods used to examine the problems mentioned are interviews (Kuhn & Macht, 2014), questionnaires (Liebl et al., 2016) or more complex experimental setups.

Two percent of Martial Arts studies are biomechanical analyses (Vieten, 2008). The movements are measured with video analysis (Lüdemann et al., 2012; Richartz, 2014; Staller & Racky, 2014) motion capture (Hofmann & Witte, 2011; Fuchs et al., 2015; Hofmann et al., 2008; Witte et al., 2010; Miyawaki et al., 2012) or inertial measurement systems (Endler, 2015; Kunze et al., 2006; Koshida et al., 2011; Cabral et al., 2010).

HEMA studies

Though a lot of literature is published about HEMA, a lot of unpublished work, around 60 % (Jaquet, 2016b), exist in HEMA. Most of the published books are about technique training and the techniques themselves (e.g. Schulze & Verhülsdonk, 1998; Schmidt, 2008a; Schmidt, 2008b; Bergner & Giessauf, 2006; Hagedorn, 2014; Lindholm & friends, 2005; Engström & Farrell, 2011). A lot can be found about the art and tradition of historical fencing (e.g. Fiedler & Wilkens, 2017; Vavra & Bauer, 2017; Leiske, 2018; Wanke, 2009). Only a few articles exist about the theory of how to do an experiment in HEMA (Jaquet & Sørensen, 2015; Jaquet, 2016a). Experimental studies were rarely executed in HEMA.

Jaquet (2016a) evaluated historical sources of the so-called Strike *flügel* and compared two different versions of it using objective and subjective criteria. Jaquet used a protocol and video footage for the evaluation.

In preparation for this thesis two experiments were carried out. First an experiment was executed which used augmented reality glasses during HEMA training (Merkert & Möller, 2017).

The goal was to improve the performance and to control the speed of the technique. This was done by showing technique videos before or during the technique performance.

After that a study about the heart rate variability in HEMA freefight was made (Merkert, 2018). I measured the heart rate and the variability to get the stress levels of the fencers during the freefight.

Farlock (2018) made an eye tracking study with experts, novices and non HEMA fighters. The main object was the difference of the perception at different experience levels.

Biomechanic studies

In Olympic fencing 451 biomechanic studies were executed (Chen et al., 2017). For these studies motion capture, force plate, EMG measurement, accelerometer and anthropometric assessments were most used. For motion capture studies, infrared-based retroreflective markers (IBRM) or electromagnetic sensor tracking systems were taken.

In HEMA, no biomechanic study is known so far. In this study knowledge from previous experiments was used. The number of repetitions in training (see Table 3.2 on page 28) and the size of the fight area (Merkert, 2018) are used in this thesis.

2.5 OPEN QUESTIONS

As mentioned in the beginning two different opinions exist about how to train in HEMA. One side trains techniques from the medieval sources as accurately as possible, the other side trains techniques which makes them survive a fight, independent of existing sources. To varify these assumptions the following questions were examined.

It was investigated which techniques were used most frequently in the freefight situation. The biomechanics of the Longsword techniques were analysed as follows. For these questions training (Part I) and freefight (Part II) situations were measured and compared to each other.

Training vs freefight - Strikes

One question is the difference between the Principles and Master Strikes in training versus Principles and Master Strikes in freefight situation. In the null hypothesis there are no significant biomechanical differences between *freefight Principles and Master Strikes* compared to the *training Principles and Master Strikes* with

the Longsword. According to the alternative hypothesis there are significant biomechanical differences in *freefight Principles and Master Strikes* as opposed to *training Principles and Master Strikes* with the Longsword.

Training vs freefight - Guards

Also important is the difference between the Wards in training versus Wards in freefight situation. In the null hypothesis there are no significant biomechanical differences between *freefight Guards* compared to the *training Guards* with the Longsword. According to the alternative hypothesis there are significant biomechanical differences in *freefight Guards* as opposed to *training Guards* with the Longsword.

Novices vs experts - Strikes

The next problem to look at is how the biomechanic differs in one Principle or Master Strike in novices or experts. How big is the difference between the same Longsword Principle or Master Strike performed by novices or experts? In the null hypothesis there is no significant biomechanical difference between *novices and experts* in the *same Longsword Principle or Master Strike*. According to the alternative hypothesis there are significant biomechanical differences between *novices and experts* in the *same Longsword Principle or Master Strike*.

Novices vs experts - Guards

And again the problem can be transfered to Longsword Wards. The question is how the biomechanics of the same Longsword Guard varies when performed by novices or experts. In the null hypothesis there is no significant biomechanical difference between *novices and experts* as opposed to the *same Longsword Ward*. According to the alternative hypothesis there are significant biomechanical differences between *novices and experts* as opposed to the *same Longsword Ward*.

The duration of every Principle and Master Strike and the maximal sword point velocity were calculated. Koshida et al. (2011) measured an average movement time (340 ms) of the kendo strike-thrust motion with a single forward step toward the target object. From a video recording in which an Oberhau[12] is performed with the Longsword in training one can measure a technique duration of 350 ms (Kohutovič, 2013). A technique duration of around 340 ms is expected in a Longsword freefight.

The maximal sword point velocity of a Longsword technique has not been measured yet. In this thesis the sword point velocity

12 a HEMA strike top downwards

of every measured technique is analysed. The maximal sword point velocity and the sword point velocity for the complete techniques were investigated.

The understanding of historical sources in HEMA can be improved by the additional information which is gained from this thesis. The extra knowledge can help fencers to train more effectively for freefight situations and improve their fighting skills.

3 METHOD

In the previous chapter European Martial Arts was described and the basic information for this thesis was given. This chapter describes the equipment and computer programs used in the experiment. The development of the experiments is presented as well as all necessary steps to prepare the measurements. The experimental setup for the first and the second experiment is described. The experimental procedure for both parts is explained. Finally, the post-processing of the data is described.

The experiment is devided into two parts. The first part is the training and the second is the freefight. The data of each fencer (only one at the time) is recorded. In the training part, the fencers see the techniques they suppose to perform with their partners.

3.1 TECHNICAL SETUP

Sensors

A combination of magnetic field, accelerometer and gyroscope sensory system was chosen for the measurement in this thesis. A combination of these three systems has a sensor recognition rate of 100 % (Pirkl et al., 2008). To minimize the costs and to have more flexibility, which is described below, this kind of system was selected.

The myon aktos-t sensory system[1] was used. This is an inertial measurement system which tracks the acceleration, the angular velocity, and the magnetic field. The system consists of 16 battery-operated sensors (see Figure 3.1 top right). They also have an on-board memory, but in order to control whether the sensors are working properly the data was sent to a digital receiver. In this case no cable had to be attached to the subject or next to it. A reception amplifier was needed to get an uninterrupted data stream for the relatively long distance of this set up. The distance is needed due to the operating range of the

1 https://www.myon.ch/

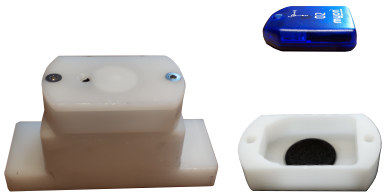


Figure 3.1: Sword-case and body-cases for sensors.

fencers and to protect the system from the fencers. The amplifier was connected to the receiver, which in turn was connected to a laptop to display the data.

In comparison to a camera based system the myon system has some advantages. Because two people are in the measurement area at the same time, the fencer and the partner, which was not measured, would cover some of the markers. Other than that the camera system of the IBRM (infraredbased retroreflective markers) needs to be placed in a room of at least 10 x 10 meters. From experience it is known that a floorspace of 7 x 7 meters is needed. Even more space (at least 9 x 9 meters) is necessary to move the Longsword unrestrained in the fight. The last meter is necessary to protect the cameras and observers from any damage. A sports hall would correspond to that, but the system was needed over the period of two months. The system would have had to be set and dismounted before and after every measurement. This would have meant an enormous amount of work.

The sensors measure with a frequency of 142 Hz. Motion studies in Martial Arts measure with frequencies of 60 Hz (infrared cameras: Miyawaki, 2012), of 100 Hz (inertial system: Endler, 2015; electromagnetic: VencesBrito et al., 2011), 200 Hz (infrared cameras: Hofmann et al., 2008; Cabral et al., 2010; video camera: Sorensen et al., 1996), or 250 Hz (infrared cameras: Witte et al., 2010; Hofmann & Witte, 2011; Witte et al., 2012; Fuchs et al., 2015). Koshida et al. (2011) measured a Kendo Strike with infrared cameras, which had a frequency of 150 Hz. Bartlett (2007) suggests a framerate of 100 Hz for quantitative analysis of activities as fast as a golf swing. This supports that a measurement rate of 142 Hz is sufficient for this study.

Casing

In order to protect the sensors from severe damage, all sen-

Table 3.1: Size and weight of the aktos-t sensor and casing.

	Width	Depth	Height	Weight
Sensor	2.4 cm	3.2 cm	0.7 cm	6 g
Casing (outer)	2.9 cm	5.0 cm	1.2 cm	14 g
Casing (inner)	2.4 cm	3.4 cm	0.9 cm	
Sword sensor casing	2.9 cm	8.0 cm	4.2 cm	92 g

sors were put in a casing (see Figure 3.1 bottom right). The size and weight of the sensors and the casing are reported in Table 3.1. The casing for the sword sensor had a thicker bottom in order to have more space between the sword and the sensor (see Figure 3.1 left). This was done because of an interference of the metal sword with the magnetic field of the sensor. Because of the thicker bottom the interferences were reduced but not avoided completely.

Position

To capture the important movements 16 sensors around the body are used altogether. To protect the sensors from any damage, they are attached to the subject in a dorsal position whenever possible. No sensors are used for the fingers, because they would not act differently from the whole hand.

The first sensor is placed on the back of the helmet. The

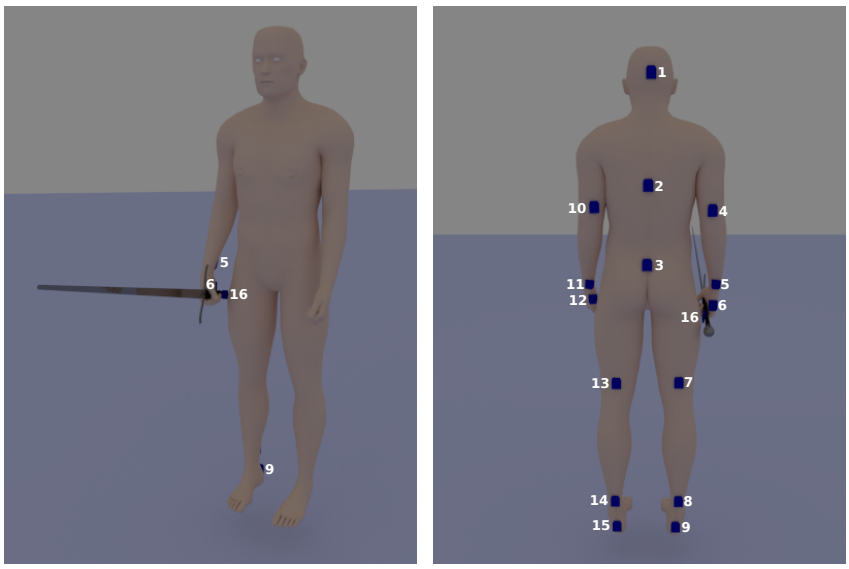


Figure 3.2: Positions of the sensors.

second sensor is placed on the thoracic vertebra 10 (T10), sensor three on sacrum 2 (S2), both on the skin. Sensors 4, 5, 6, 10, 11 and 12 are also attached to the skin. Sensors 7, 8, 9, 13, 14 and 15 are placed on the clothes or shoes. The sensors on the arms and legs were placed distally. The sensors on the hand are placed on the ulnar side. Sensor 16 is aligned to the flat side of the blade. The positions of all sensors are marked in Figure 3.2.

Further hardware

To present the technique videos in part I (training) and the order of the next fighters in part II (freefight), a projector, a screen and a second laptop (hp EliteBook) are used. The screen has a width of 186 cm and a height of 105 cm. It is positioned at a height of 210 cm.

In part II of the experiment two additional cameras are used to record the fights. Both of them are GoPro cameras (GoPro HERO CHDHA-301 & GoPro HERO4 Black). They are positioned on tripods at a height of 140 cm.

3.1.1 *Software*

The software utilised for the pre-processing, the measurement, the post-processing and the analysis is listed in this section.

Pre-processing

The video for displaying to the fighters are cut with Avidemux (GTK+). The order of the sequence is calculated by an Octave script.

Measurement

To control the sensory system during the measurement the Matlab based software IMU_v6 from the Neurocognition and Action Group - Faculty of Psychology and Sports Science - University of Bielefeld is used. It is a specific software for measurements with the myon aktos-t system. For the stimuli presentation in part I the VLC media player 2.2.1 is used.

Post-processing

For the data annotation a custom rendering engine is used (Waltemate et al., 2015). It is also used for motion annotation (de Kok et al., 2015). The renderer supports shadows, high quality character rendering and more. For this work a frame rate of 60 Hz is used. This is sufficient for real time replay of the movements to be annotated.

Analysis

The motion analysis is made in Python. Parts of the script from the Graphics & Geometry Group - Faculty of Technology - University of Bielefeld are used for this (Waltemate et al., 2015; Hülsmann et al., 2017; Hülsmann et al., 2018). Statistical analysis is made in R.

3.2 PREPARATION OF THE EXPERIMENT

For every experimental day the experiment needed to be set up and dismounted. To ensure that the setting was always identical, the lines of the sports hall floor were taken as marks. The fighting and training area is surrounded by 32 mats[2] (see Figure 3.3). They are placed in a corner of the hall as a square. On the corner of the fighting area, diagonally opposite the corner of the sports hall, the techical equipment is installed (see Section 3.3).

After all equipment is set up, the sensory system has to be configured. The sensors are put on a body model. To calibrate the system all sensors are aligned along a ruler. For magnetic field calibration all sensors are put on top of a solid box. Then the investigator goes into the fighting area with the sensors on the box and mills around in the area. While walking in the area the box needs to be turned evenly around in at least two dimensions. When the investigator has milled around in every part of the fighting area the magnetic field calibration is done. The system is now ready for use.

3.3 SETUP OF THE EXPERIMENT

To improve the measurements from the sensors, one corner of the gym is chosen for the experiment. The recording area has a size of 7 x 7 meters.

The setup for the first part can be seen in Figure 3.3. In part I a laptop, an amplifier (vis-à-vis to the corner of the sports hall), and a receiver for the myon sensors are placed next to the recording area. A projector and a screen (186 cm x 105 cm) are placed next to the recording area. The participants perform the techniques on a line parallel to the screen. This screen position

2 inner area has size of 7 x 7 meters

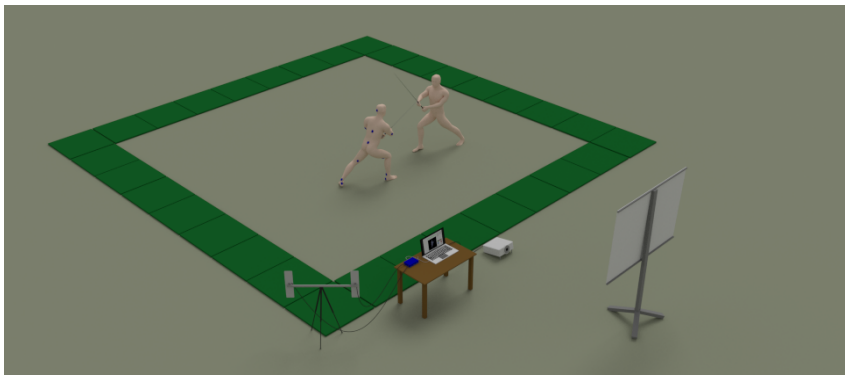


Figure 3.3: Experimental setup of part I.

is chosen because both participants are able to look at the screen in the training sequences with little effort.

The setup for the second part can be seen in Figure 3.4. In part II the recording area also has a size of 7 x 7 meters. The laptop, amplifier and receiver for the myon sensors are placed next to the recording area like in part I. Additionaly two GoPro cameras are put at two adjacent sides (left and right of the amplifier) of the fighting area to document the fights for later evaluation. The projector and the screen are placed differently to the setup in Experiment I, so that every participant and the investigator are able to see the next three fighters, which are written on there.

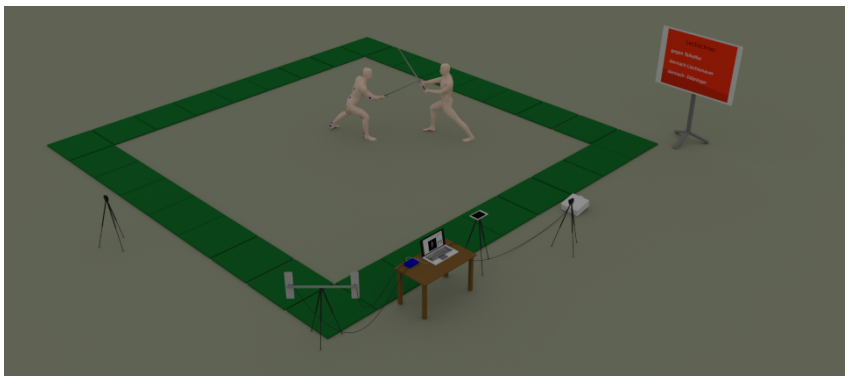


Figure 3.4: Experimental setup of part II.

3.4 PROCEDURE OF THE EXPERIMENT

The measurements are divided into a questionnaire and two measurement parts. In the first part, the techniques of the training are measured. In the second part the freefights are measured. The techniques and fight orders are randomised for every participant.

3.4.1 *L-pose*

The L-pose (see Figure 3.5) is needed to calibrate the sensors for the participant. To get the best measurement the subject needs to perform the L-pose before every trial (see Section 3.4.3 & Section 3.4.4). In the L-pose the subject has to spread his legs so that the feet are directly under the hip. The toes are directed ventrally, legs are straight. The upper part of the body is standing upright. The upper arm is hanging down, the ellbows are bent at 90 degrees, so that the lower arms are parallel to each other and directed ventrally. Hands make a fist with the thumbs directed cranially. The sword is held in the right hand, so one only needs to put the left hand on the sword and could start fighting immediately. The blade is held with the strong side ventrally, the point and the pommel of the sword are in a vertical line. The head is looking ventrally and is not bend forward or backwards.

3.4.2 *Questionnaire*

All test persons fill out a questionnaire (see Chapter F) to get demographic data as well as the preferred weapons, Guards and techniques. There are also ten questions to get an impression of what the people think how they behave in a freefight. The length of all body segments used is also measured.

3.4.3 *Part I*

All participants are put together in groups of two. In these groups the test persons perform the first part of the experiment.

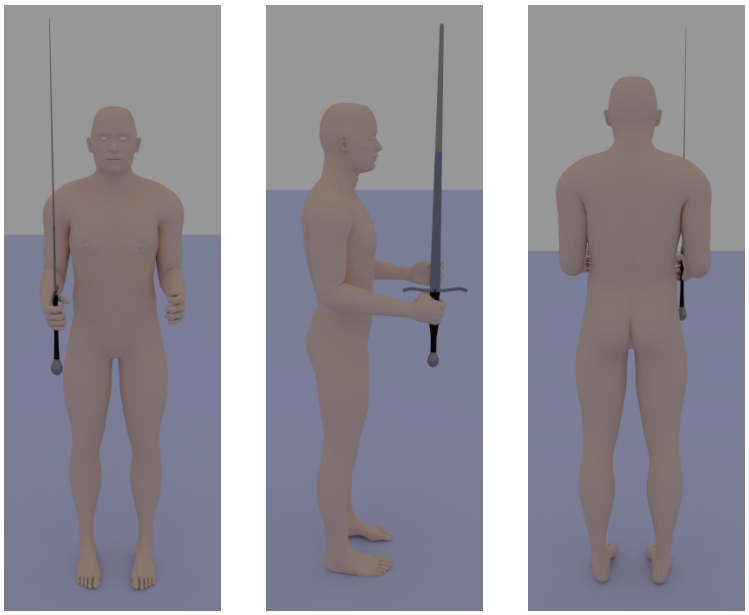


Figure 3.5: L-pose position.

Because of an odd number of participants one person is put in two groups, so that there are five groups of two in total.

The participant with the sensors does six Guards without the partner. First the investigator names the Guard and the subject gets to see the name and a video of the first Guard, left and right side, for five times. Then he tries out the Guard three times. After that the participant performs the L-Pose (see Figure 3.5), the sensors are aligned and the L-pose capture is made. Then the recording is started and the subject performs the Guard six times on each side. After that the test person gets into L-pose again. The measurement is stopped and the next Guard is shown (see Figure 3.6).

After the six Guards the subject performs 21 Strike variations with the other group member as partner in 60 to 90 minutes. The investigator calls the name of the first technique variation and the group gets to see the technique variation name and a video of it five times on a screen. The person with the sensors executes the technique which is shown on the right side of the screen. The partner allows the fighter to execute the technique as planned. That means that he has to make specific mistakes so the sensored praticipant can successfully finish his technique. The error which should be performed is executed by the left

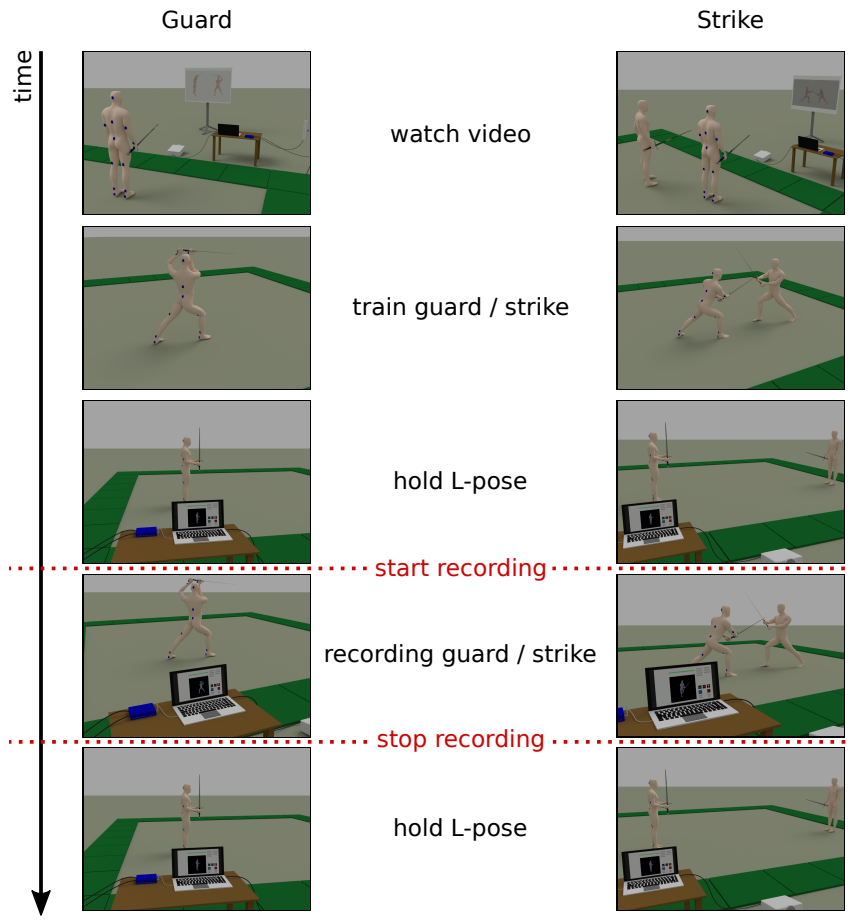


Figure 3.6: Timeline for one trial in part I of the experiment for the Guards and Strikes.

person in the video. The two fighters try out the named and seen technique variation five times. To do that, they separate to a distance of 3 m. After they have a go at the technique, the sensored subject gets into the L-pose, the sensors are aligned, the L-pose capture is made and the measurement is started. Then the subject performs the technique six times. When one of the six techniques is performed badly or a wrong technique is performed, the number of the technique is written down and one more technique is executed before the L-pose is made. After that, the recording is stopped and the next technique variation is shown (see Figure 3.6).

Before the participants start with the measurement, they are told that it is not important how fast they do the techniques but that the techniques have to be done correctly and properly.

The techniques are chosen by two HEMA experts. All techniques are randomised for every participant. The utilised technique videos were created by Drey Wunder as learning aid for Longsword techniques.

In Martial Arts motion analysis different amounts of repetitions are used (see Table 3.2). Bartlett (2007) suggests 10 trials for a group of 10 performers for reasonable statistical power. To reduce the measurement time for each participant but keep the technique variations high only six repetitions per technique were made.

Table 3.2: Number of movement repetitions and group sizes in different biomechanical Martial Arts studies. R = Repetitions; GS = Group size; B = Boxing; Ke = Kendo; TC = Tai Chi; S-D = Self-Defense; Ka = Karate; KF = Kung-Fu.

Author	Year	Sport	Technique	R	GS
Cabral et al.	2010	B	Upper Cut	3	1
Koshida et al.	2011	Ke	strike-thrust motion	3	15
Miyawaki et al.	2012	Ke	Kicking	3	2
Kunze et al.	2006	TC	different movements	5	2
Fuchs et al.	2015	S-D	Fist Punsh	5	4
Hofmann et al.	2008	Ka	Gyaku-Zuki	6	3
Hofmann & Witte	2011	Ka	Gyaku-Zuki	6	3
Witte et al.	2010	Ka	Mae-Geri	10	5
Witte et al.	2012	Ka	Mae-Geri	10	5
VencesBrito	2011	Ka	Choku-Zuki	20	18
Endler	2015	KF	Arm techniques	20	6

3.4.4 *Part II*

In the second measurement part, every fighter has to fight against every other participating fighter. For every subject one hour is planned for preparing the subject and measuring the fights. All fights are measured on three different days.

The participants are told the rules under which they will fight against each other. All fights are performed under the HALAG

3W rules (see Section 2.3). The fighters have a battle area of 7 x 7 meters. All fights are captured with two GoPro cameras and the myon aktos-t sensors.

One fighter is marked with 16 sensors. Then he puts on his fighting gear (see Section 2.3). The sensored person has to make 32 fights in a row[3]. One fight corresponds to one trial. In every trial the sensored participant executes the L-Pose, the sensors are aligned, the L-pose capture is made and the measurement is started. The cameras begin recording. The fight starts and has finished when one of the fighters ends the fight. Then the measurement and the camera recording is stopped. The fighters scan their status in the CHALLENGE·3W app. The trial then ends. The trial sequence is shown in Figure 3.7. When the fencers are ready, the next trial begins. This goes on until the fencer finished all 32 fights.

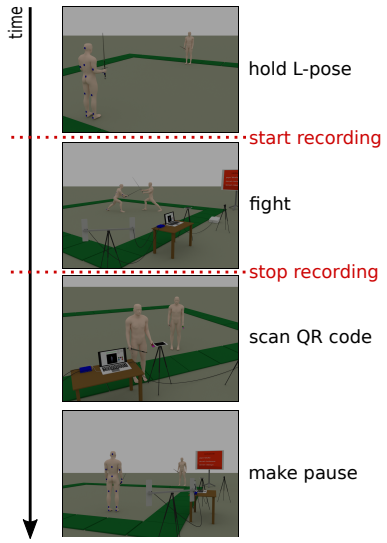


Figure 3.7: Timeline for one trial in part II of the experiment.

The opponents of the sensored person get the succession from a screen where the next three opponents are shown.

The fighters are told that they should fight like they usually do in freefight and not add any special techniques they normaly do not use. Throws are not allowed in order to protect the sensors.

3 32 in a row mode

To make the exhaustion in fights comparable and in order not to lose too much time by putting the sensors on and off the fencers, the freefight mode *32 in a row* is choosen. The preparation of one fighter takes about 20 min. For each trial 1 min and 15 sec is planned. This time was estimated on empirical values of fights in this mode (Merkert, 2018). One fight takes about fifteen seconds. Afterwards the fencer has one minute to rest. Schunder (2012) found out that the average length of an active period is around six to 20 seconds long. After such an active phase a fight normally ends when fighting under the rules of HALAG 3W. Every fencer has 32 fights, so that the sensored fencer fights four times against every participant.

3.5 POST-PROCESSING

For post-processing, the data of the sensors and the fight results are calculated, which is described in this section.

3.5.1 *Sparring results*

Both fighters can leave a fight with the status *unharmed* (3 points), *injured* (2 points) or *dead* (1 point). The status/points for both fighters are saved to a database. To get a ranking for the 32 fights in a row, the following steps are necessary: sum up the points of fighter 1 ($\sum$ fight results fighter 1). Then sum up the points of the opponents of fighter 1 ($\sum$ fight results opponent of 1). The following formula calculates the ratio for the ranking of fighter *i*:

$$ratio\ ranking\ fighter\ i = \frac{\sum fight\ results\ opponent\ of\ i}{\sum\ fight\ results\ fighter\ i}$$

The ratio ranking is calculated for every fighter. The lower the value the better the fencer. If the ratio ranking is smaller than 1, the fighter kills or injures more people then he is killed or injured. If the ratio ranking is larger than 1 the opposite is the case.

3.5.2 *Movement analysis*

To analyse the movements of the fencers Dynamic Time Warping (DTW) is used. It can be used for comparison of complex movements like fencing.

Dynamic Time Warping (DTW)

DTW is used to analyse two time-dependent sequences. It finds an optimal alignment between the two sequences[4].

Algorithm

X and Y are time-dependent sequences with $Y = (y_1, y_2..., y_M)$ as the reference technique and $X = (x_1, x_2..., x_N)$ as the test motion. X has the length $N \in \mathbb{N}$ and Y has the length $M \in \mathbb{N}$. These sequences consist of feature sequences. The feature sequences ($\mathcal{F}$) are samples at equidistant points in time. This means $x_n, y_m \in \mathcal{F}$ for $n \in [1 : N]$ and $m \in [1 : M]$. The local cost measure $c : \mathcal{F} \times \mathcal{F} \to \mathbb{R}_{\geq 0}$ compares two different features. For similar sequences x and y the cost $c(x, y)$ is small and rises if they differ more.

All element pairs of the sequence are calculated, to get the cost matrix $C \in \mathbb{R}^{N \times M}$ defined by $C(n, m) := c(x_n, y_m)$. After that an alignment between X and $Y$with minimal overall cost, called (N, M)-warping path, is searched. The (N, M)-warping path is a sequence $p = (p_1, p_2..., p_L)$ with $p_l = (n_l, m_l) \in [1 : N] \times [1 : M]$ for $l \in [1 : L]$. The following conditions must be satisfied for DTW (Tormene et al., 2009): The first is the start-point constraint which anchores the warping curve at the origin. The second is the end-point constraint. It means that the global alignment is required and that the mapping covers both time series completely. Monotonicity is the third constraint, which means that an element of X has a corresponding element of Y. Last there is the local slope constraint. It says that only certain relationships, known as step patterns, are allowed between consecutive points in the warping curve.

Taking the warping path p between X and Y related to the local cost measures c, the total cost $c_p(X, Y)$ is calculated by $c_p(X, Y) := \sum_{l=1}^{L} c(x_{n_l}, y_{m_l})$.

4 This part referes to Müller (2007).

To get the optimal warping path, the minimal (N, M)-warping path ($c_{p,opt}$) needs to be determined. It is also called *DTW cost*. The way to do it refers to Müller (2007).

Usage

In order to analyse the motion performance, the motor actions need to be separated into movement sequences. One sequence is one repetition of one fencing technique. This technique is represented by feature vectors. The feature vectors are measured as angular velocity.

After the measurements, the movements from part I and II were annotated manually by one HEMA expert. To compare the techniques in training and freefight a Representative Movement (RM) was calculated. To determine the RM the mean of the evaluated motion cost ($m_{tech,dtw}$) was calculated for all six technique repetitions of one participant by

$$m_{tech,dtw} := \frac{\sum_{i=1}^{K} c_{p,opt}(Z)}{K}$$

with $Z = (z_1, z_2..., z_K)$. Z has the length $K \in \mathbb{N}$. Because techniques are more equal the smaller the value, the minimum mean motion cost of the technique was taken as RM. Then the techniques of the fights are compared to the RM of every technique (intraindividual).

For the comparison of the experts and the novices the RMs of the same techniques were compared for all nine subjects (interindividual).

Table 3.3: Body segments for Swordpoint translation velocity calculation.

From	To
Sacrum 2 (S2)	Thoracic vertebra 10 (T10)
Thoracic vertebra 10 (T10)	Shoulder
Shoulder	Elbow
Elbow	Wrist
Wrist	Middle of the hand
Middle of the hand	Point of the sword

Swordpoint velocity (SPV)

The myon system measures angular velocities. This thesis is interested in the translation velocity of the swordpoint. To transform the angular velocity into translation velocities the length of the body segments (see Figure 3.8) listed in Table 3.3 of every participant must be known.

Because no root translation is measured, the global SPV may be even higher than the calculated local SPV.

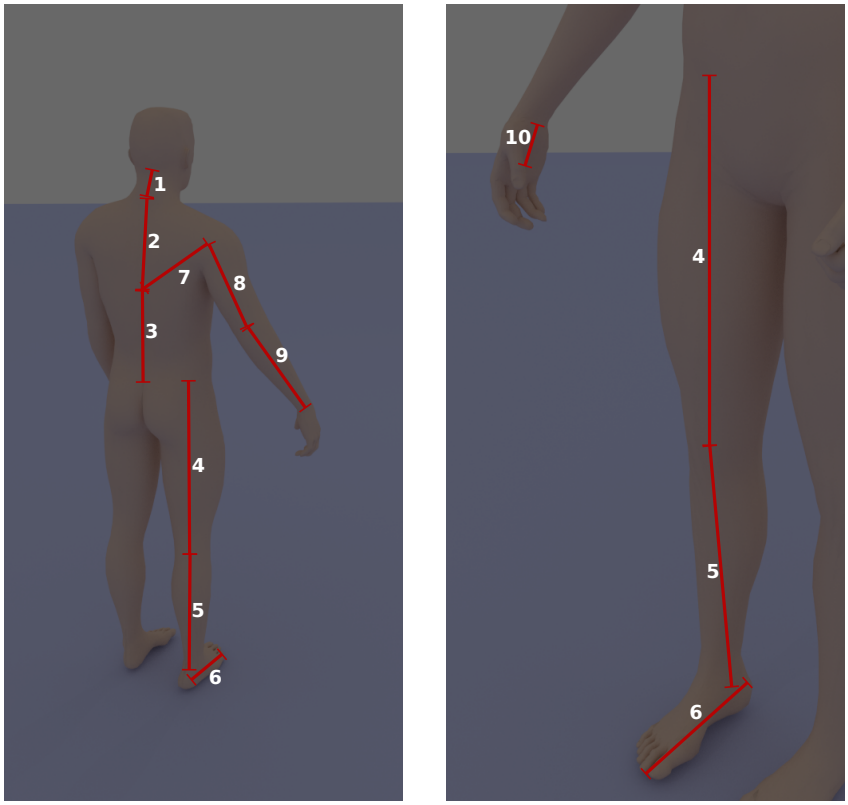


Figure 3.8: Measured proportions of the subjects; 1: inion to C7; 2: C7 to T10; 3: T10 to S2; 4: S2 to knee; 5: knee to ankel; 6: ankel to toe; 7: T10 to shoulder; 8: shoulder to elbow; 9: elbow to wrist; 10: wrist to middlehand.

4 RESULTS

In the previous chapter the used equipement, the experimental procedure and the analysis algorithms were described. In this chapter the demographic data are displayed. The segment length and the fight results of every participant are summarised. The sparring and training is analysed in details. To do this every technique is counted and the duration is calculated. The freefight duration as well as the swordpoint velocities in training are examined. The technique recognition rate of the computer is calculated. Finally a look at the distances of the movements is made. All data were statistically analysed.

In this chapter, all data is tested for normal distribution. If the data is not normally distributed the Wilcoxon-Mann-Whitney test is used. To simplify the tables the column is named t(df), but if the data is not normally distributed the U value is written in there. The significe level is adapted to the Wilcoxon-Mann-Whitney test.

4.1 PARTICIPANTS

In this thesis nine European martial artists are examined. They are all male fighters at an age of 27 to 47 (median = 40). They are all right-handed. Four of the fencers have practised for one to two years, four have trained for five to six years and one fighter has fenced for ten years. The subjects are divided into two groups. Group one are the people with less than three years of fencing, which makes them Novices. The other five fencers are the Experts group. All nine participants have trained between one and three hours and have fought up to ten freefights every week. Seven of the subjects go to at least one HEMA competition a year. The favourite HEMA weapon of 8 out of 9 participants is the Longsword.

4.1.1 *Prefered techniques*

The *From the Roof* is the favorite Guard of four participants. Three fencers do not have a preferred Guard. The other two prefer the *Fool* and the *Plough*. When asked which Guards the fencers use during a freefight all named *From the Roof*, the *Fool* and the *Plough*, six fencers called the *Ox*, three mention the *Barrier guard*, two named the *Side guard* and the *Long point* and one fencer calls the *Key*.

The *Range strike* is the favorite technique of two fencers. One fencer has the *Setting Off* and the *Twitching* as preferred technique. All other fencers have no favorite technique. The Principles and Master strikes which the fencers think they use during a freefight are summarised in Table 4.1.

Table 4.1: Number of fencers who think they use the Principle or Master strike in a freefight.

Principle	Fencers	Master strike	Fencers
Following After	7	Range strike	8
Setting Off	6	Cross strike	7
Twitching	6	Crooked strike	3
Taking Off	5	Scalp strike	3
Changing Through	5	Squinting strike	2
Mutating	5		
Doubling	4		

4.1.2 *Freefight behaviour*

The fencers say that they perform more techniques in freefights which are described in historical sources then making their own techniques. The participants report that they fight neither defensive nor offensive in freefights. They think they use neither many different techniques nor few different techniques. The fencers also report that the Guards are not changed very often but also not too rarely.

4.1.3 *Proportions*

The fighters train and fight with the same sword with the total length of 1.27 m and a weight of 1.9 kg. The length of the blade is 0.95 m. The cross has a size of 25.5 cm.

For every participant the segment lengths are measured as described in Subsection 3.5.2. The mean segment lengths are summarised in Table 4.2. The segment lengths of every participant can be seen in Table B.6.

Table 4.2: Mean proportion measurement of the subjects in cm.

No	Name	Mean	SD
1	Inion to C7	11.33	1.50
2	C7 to T10	26.56	2.40
3	T10 to S2	29.44	4.30
4	S2 to knee	51.00	3.04
5	Knee to ankle	47.89	2.26
6	Ankle to toe	27.11	1.62
7	T10 to shoulder	29.11	4.04
8	Shoulder to elbow	31.89	3.14
9	Elbow to wrist	27.56	2.01
10	Wrist to middlehand	6.61	0.49
11	Middlehand to swordpoint	104	0.00

4.1.4 *Fight results*

The fight results are summarised in Table 4.3. In addition to the ranking the level of expertise is written in the table. The level of expertise is calculated by the fencing age and the mean time of training per week. The experts have a better ranking than the novices. Exceptions are the first and the 7th place.

All fencers usually fight according to the rules of HALAG·3W. Three of the participants *killed* and *injured* more people in the fight as they themselves were *injured* or *killed*. For all the other fencers it is the other way round.

Table 4.3: Ranking of the freefights for the 32 fights in a row and experience level of the subjects.

Rank	VP	Ratio ranking	Level of expertise
1	8	0.70	Novice
2	1	0.73	Expert
3	3	0.87	Expert
4	5	1.06	Expert
5	7	1.10	Expert
5	6	1.10	Novice
7	2	1.16	Expert
8	9	1.30	Novice
9	4	1.38	Novice

4.2 FREEFIGHT TECHNIQUE COUNT

In freefight 175 Principles (5 different), no Master Strikes and 1603 Guards (all 6 different) are annotated by the expert. 942 attacks can not properly be allocated to any Principle or Master Strike. 414 of the unallocated attacks can be identified as Master Strikes. 545 of the Guards made in freefight can not be allocated to any of the six investigated Wards. The summed up number of Principles of all subjects performed in the freefights is illustrated in Table 4.10 on page 45. In Table B.1 on page 83 the number of the identified Principles and Wards for each participant can be seen.

4.3 TECHNIQUE RECOGNITION RATE

To get a technique recognition rate for freefight techniques, the DTW is calculated for every annotated freefight technique against all training techniques. Figure 4.1 depictures an example with the Twitching as freefight technique. The DTW is calculated for *Twitching* and for all other techniques made in training (Figure 4.1 & 4.2 are extracts from the analysis). For every technique combination of Freeefight and training a DTW cost value is computed. Now the minimal DTW value of *Twitching* (freefight) is searched. In Figure 4.1 the minimum DTW value is calculated

for the training technique *Twitching*. This means, the computer found the same technique as the expert.

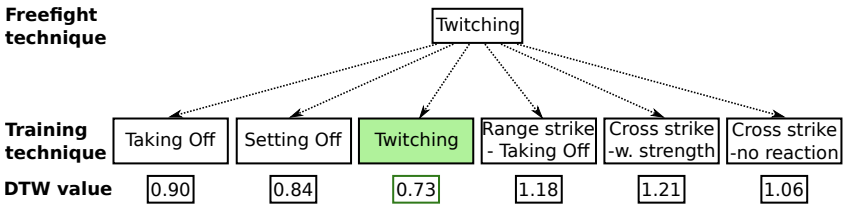


Figure 4.1: Minimal value of the DTW-based classification equals technique annotated by expert.

In Figure 4.2 the next technique of the freefight is analysed. It is *Setting Off*. The DTW is calculated for this technique with every other training technique as described below. But this time the minimal DTW value is found for the technique *Twitching*. This means the expert and the computer calculation find different techniques. These differences are described in this part.

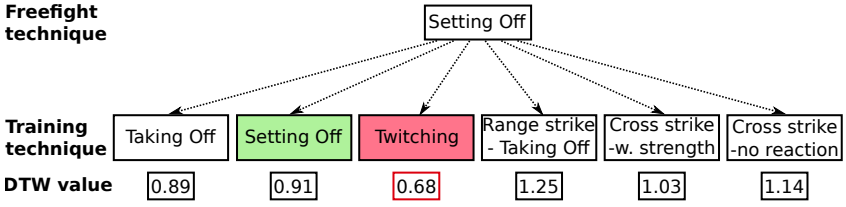


Figure 4.2: Minimal value of the DTW-based classification unequals technique annotated by expert.

Because the odds are not fifty-fifty the maximum predicted hit rate (MPHR) is calculated. The MPHR depends on the ratio of Guards and Strikes.

In the first step all techniques that are recognized without doubt by the expert are compared to the technique names. 45 % (sd = 18 %) of the Guards are recognized as the same technique from the expert and the minimal value of the DTW-based classification. This recognition rate is not significantly different from the (MPHR) of $\frac{12}{33}$ or 36 % ($t(8) = 1.44$; $p = 0.189$). The hit rate of 3 % (sd = 6 %) for the Strikes is significantly lower compared to the MPHR of $\frac{21}{33}$ or 64 % ($t(8) = -32.69$; $p < 0.001$).

In a second step all techniques where the expert could make a difference between Strike and Guard (including the techniques

from the first step), are analysed. The techniques which are recognized as Guards by the expert are sorted as Guards by the minimal DTW cost value in 69 % (sd = 22 %). This recognition rate is significantly higher than the MPHR for Wards ($t(8) = 4.62$; $p = 0.002$). The hit rate of 74 % (sd = 31 %) for the Strikes is not significantly higher or lower than the MPHR for them ($t(8) = 1.04$; $p = 0.327$).

Now only the techniques which are recognised by the expert as Guards or Strikes but no other information is given (techniques from step two without techniques from step one), are analysed. Those *unknown techniques* have the following hit rates. The Guards have a hit rate of 53 % (sd = 21 %). This recognition rate is significantly higher than the MPHR for Guards ($t(8) = 2.31$; $p = 0.049$). For the Strikes, the MPHR is significantly lower than the recognition rate of 85 % (sd = 12 %) for the Strikes ($t(8) = 5.25$; $p < 0.001$).

4.4 MOVEMENT ANALYSIS

The DTW costs for a technique is calculated to get the distance between two motions. The smaller the DTW cost the more related are the motions.

The DTW values for training are calculated between the technique repetitions of one technique and subject. For the fight the DTW costs are calculated between the reference technique[1] and the freefight technique of one fencer.

4.4.1 *Training*

The overall mean for the DTW costs of all Guards in training is 0.06 (sd = 0.04). In Table B.4 the training data of all measured Wards for every subject is summarised. All Strikes have a mean DTW cost of 0.09 (sd = 0.02). The Strike DTW costs for every participant in training is summarised in Table B.3.

In Table 4.4 all Guards which are made in the sparring are summarised. It shows the weighted mean of the Guards made in

1 technique which has compared to the other technique repetitions the smallest mean DTW value

Table 4.4: Weighted mean of DTW costs and SD over all participants in training and sparring for Wards.

Guards	**Training**		**Fight**	
	Mean	SD	Mean	SD
Fool – left	0.04	0.03	0.75	0.12
Fool – right	0.03	0.01	0.94	0.27
Ox – left	0.03	0.01	1.02	0.33
Plough – left	0.03	0.01	0.86	0.19
Plough – right	0.03	0.01	0.81	0.28
Barrier guard – left	0.19	0.28	1.53	0.37
Barrier guard – right	0.04	0.01	1.23	0.61
From the roof – left	0.08	0.02	0.96	0.01
From the roof – right	0.06	0.05	0.84	0.22

training. The Overall DTW cost mean of the Wards from training in Table 4.4 is 0.06 (sd = 0.05).

The DTW cost mean of the strikes made in the freefight from training is 0.09 (sd = 0.01).

4.4.2 *Fight*

The mean DTW cost for Guards in sparring is 0.99 (sd = 0.25). In Table 4.4 the mean of the DTW costs for every performed Guard in sparring is summarised.

The Strikes performed in freefight have a mean DTW cost of 1.05 (sd = 0.17). The mean DTW costs for every sparring technique is summarised in Table 4.5. In Table B.5 the sparring data of all performed techniques for every subject is combined.

Table 4.5: Weighted mean and SD over all participants of DTW costs in training and sparring for Strikes.

Strikes	**Training**		**Fight**	
	Mean	SD	Mean	SD
Taking Off	0.09	0.05	0.97	0.18
Setting Off	0.07	0.02	1.18	0.22
Changing Through	0.11	0.04	1.20	0.30
Following After	0.10	0.01	0.84	0.29

Table 4.6: Unpaired t-test results for DTW costs for Strikes and Guards in sparring; Norm = Normal distribution; df = Degrees of Freedom; t = T-test result; sig = Significant.

VP	Norm	df	t(df)	p	sig
1	X	10	-0.83	0.424	X
2	X	3	-0.25	0.819	X
3	✓	12	0.92	0.378	X
4	✓	10	-0.37	0.720	X
5	✓	8	-0.36	0.729	X
7	X	9	-0.93	0.763	X

For the subjects 1, 2, 3, 4, 5 and 7 the DTW costs do not differ significantly for the Guards in sparring from the Strikes in sparring (see Table 4.6). The subjects 6, 8 and 9 are excluded from this analysis because they only performed one or two different Strikes.

4.4.3 *Techniques*

For comparing the DTW of training with sparring the weighted mean for the training DTW costs is calculated because not every participant executed all techniques. Otherwise no comparison of the data is possible.

By comparing the Wards of all subjects from training and

Table 4.7: Paired t-test results for DTW costs for Guards in training and sparring; Norm = Normal distribution; df = Degrees of Freedom; t = T-test result; sig = Significant.

VP	Norm	df	t(df)	p	sig
1	X	10	-7.02	<0.001	✓
2	X	10	-17.92	<0.001	✓
3	X	8	-5.71	<0.001	✓
4	✓	6	-7.19	<0.001	✓
5	X	6	-8.52	<0.001	✓
6	X	5	-7.12	<0.001	✓
7	✓	7	-7.59	<0.001	✓
8	✓	6	-10.68	<0.001	✓
9	✓	5	-71.89	<0.001	✓

Table 4.8: Paired t-test results for DTW costs in freefight compared to training; Norm = Normal distribution; df = Degrees of Freedom; t = T-test result; sig = Significant.

Guard	Norm	df	t(df)	p	sig
Fool - left	✓	9	16.67	<0.001	✓
Fool - right	✓	7	8.89	<0.001	✓
Ox - left	✓	6	9.33	<0.001	✓
Plough - left	✓	9	9.94	<0.001	✓
Plough - right	✓	8	8.65	<0.001	✓
Barrier guard - right	✓	4	3.42	0.027	✓
Barrier guard - left	X	5	3.25	0.023	X
From the roof - right	✓	9	10.30	<0.001	✓

freefight intraindividually (see Table 4.4), the training Guards have significantly smaller DTW costs then the sparring Guards (see Table 4.7). For the Strikes this kind of analysis does not make sense because the number of repetitions was too low.

The techniques made in sparring are compared to the ones from training. Significantly higher DTW costs in freefight than in training are found in *Taking Off* (t(4) = 10.59; p = <0.001), *Setting Off* (t(7) = 13.88; p = <0.001), *Changing Through* (t(5) = 7.62; p = <0.001) and *Following After* (t(7) = 7.45; p = <0.001). All other Strikes are not tested because the number of subjects who made the Strike is too low.

Table 4.9: Paired t-test results for DTW costs for techniques in training and sparring for every subject; Norm = Normal distribution; df = Degrees of Freedom; t = T-test result; sig = Significant.

VP	Norm	df	t(df)	p	sig
1	X	16	11.34	<0.001	✓
2	X	13	20.25	<0.001	✓
3	X	13	7.77	<0.001	✓
4	X	11	10.70	<0.001	✓
5	X	12	11.08	<0.001	✓
6	✓	6	8.24	<0.001	✓
7	X	12	10.44	<0.001	✓
8	X	8	9.23	<0.001	✓
9	X	7	87.12	<0.001	✓

For Guards significantly higher DTW costs in freefight compared to training are found in *Fool - left*, *Fool - right*, *Ox - left*, *Plough - left*, *Plough - right*, *Barrier guard - right* and *From the roof - right* (see Table 4.8). No significant difference is found in *Barrier guard - left* because the data is not normalised.

When looking at all techniques for every participant individually the DTW costs for techniques in training are significantly lower compared to the DTW values in sparring (see Table 4.9).

4.5 TECHNIQUE DURATION

The motions' beginning is defined as the first sword movement. The movement ends when the technique has been performed and the sword is pulled back to the fencer (who made the technique).

4.5.1 *Training*

The mean duration for Principles and Master Strikes is shown in Table B.2. The mean duration for all Principles and Master Strikes is 1.84 s.

Short techniques are the *Crooked strike - against upper strike* (t = 1.40 s; sd = 0.20 s), *Following After* (t = 1.34 s; sd = 0.35 s), the *Scalp strike - against the Fool* (t = 1.37 s; sd = 0.20 s), the *Cross strike - no reaction* (t = 1.40 s; sd = 0.23 s) and the *Range strike - against Upper strike* (t = 1.37 s; sd = 0.24 s). Techniques which take longer to execute are *Changing Through* (t = 2.62 s; sd = 0.50 s), the *Scalp strike - against the Crown with Upper* (t = 2.85 s; sd = 0.44 s), the *Range strike - Changing Through* (t = 2.63 s; sd = 0.50 s) and *Twitching* (t = 2.20 s; sd = 0.57 s).

The duration of the Guards is not summarised here because during training the duration can vary a lot depending on the task.

4.5.2 *Sparring*

The mean technique duration for the five Principles found in freefight is shown in Table 4.10. The mean duration for all Prin-

Table 4.10: Weighted mean and SD of duration (in s) of found Principles in sparring during training session (count = 6) and freefight over all participants.

Strikes	**Training**		**Fight**		
	Mean	SD	Mean	SD	Count
Taking Off	1.61	0.28	0.98	0.27	11
Setting Off	1.66	0.21	1.09	0.24	81
Changing Through	2.62	0.22	1.03	0.24	63
Mutating	1.75	0.00	1.12	0.18	5
Following After	1.43	0.24	1.21	0.42	15

ciples of Table 4.10 in freefight is 1.09 s. The mean duration for the same Principles in training is 1.89 s. Table 4.10 shows, that all techniques used in the sparring are significant faster than in training ($t(4) = 3.18$; $p = 0.033$).

The duration of the Guards in sparring is summarised in Table 4.11. Guards which are held for less than a second are the *Fool -right*, the *Side guard - right*, and the *Ox - left* and *right*. *From the roof - left* takes over two seconds. The only Guard which is not performed in the freefight is the *Side guard - left*.

Table 4.11: Mean and SD of duration (in s) of found Guards in sparring over all participants.

	Mean	SD	Count
Fool - left	1.10	0.53	198
Fool - right	0.91	0.54	49
Side guard - right	0.40	0.00	1
Ox - left	0.69	0.48	32
Ox - right	0.96	0.00	1
Plough - left	1.72	0.73	574
Plough - right	1.06	0.53	147
Barrier guard - left	1.90	0.95	12
Barrier guard - right	1.52	0.96	58
From the roof - left	2.19	0.00	66
From the roof - right	1.77	1.18	180

4.6 FIGHT DURATION

The duration of all fights of the experiment per subject is summarised in Table 4.12. The mean duration of the fights for all participants is 24.96 s (sd = 4.79 s). The shortest fight takes 7.75 s. The quickest fights take on average 11.08 s (sd = 3.61 s). The longest fight is 88.99 s. The mean of the longest fights of every subject is 54.30 s (sd = 16.57 s).

Table 4.12: Summary of fight duration for every participant.

VP	Mean	SD	Minimum	Maximum
1	21.39	7.58	10.87	45.40
2	25.78	6.63	15.60	47.61
3	34.22	10.87	18.52	56.57
4	27.55	16.44	8.86	88.99
5	22.16	9.38	8.25	49.43
6	25.84	9.95	7.75	48.92
7	24.43	12.72	9.36	65.23
8	16.81	3.78	10.67	28.29
9	26.49	12.42	9.86	58.28

4.7 SWORDPOINT VELOCITY

The SPV is calculated as described in section 3.5.2. Every technique has a unique SPV. For the Guards the SPV is close to zero. The mean of maximal velocity of all Principles and Master Strikes for all subjects is 11.13 $\frac{m}{s}$. The technique with the highest SPV is the *Cross Strike - attack the openings* with a mean velocity of 14.09 $\frac{m}{s}$ (sd = 1.80 $\frac{m}{s}$). Techniques with a slower maximal SPV are those which are stitches like *Mutating* (v = 9.20 $\frac{m}{s}$; sd = 1.18 $\frac{m}{s}$), *Twitching* (v = 9.28 $\frac{m}{s}$; sd = 0.99 $\frac{m}{s}$) or the *Squinting Strike - against Long Point* (v = 9.05 $\frac{m}{s}$; sd = 1.86 $\frac{m}{s}$).

The maximum SPV is in mean achieved at 520 ms after the first sword movement. The shortest time for maximal SPV is made with the *Crooked strike - feint* at 370 ms (sd = 80 ms). Techniques with the latest maximal SPV are *Taking Off* (t = 0.71 s; sd = 0.18 s) and the *Cross strike - attack the openings* (t = 0.77 s; sd = 0.21 s). The maximum SPVs and the duration from the

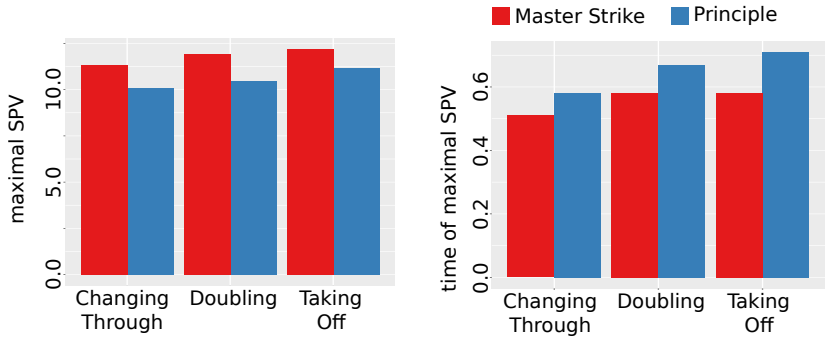
motion start to the maximum SPVs are summarised in Table B.2. There is no significant correlation between the Strike duration and the maximal SPV (t(19) = -0.61; p = 0.551; cor = -0.14). There is also no significant correlation between the time of maximum SPV and the maximal SPV (t(19) = 0.51; p = 0.614; cor = 0.12).

Comparing the technique pairs of *Taking Off*, *Doubling* and *Changing Through* the Master Strikes always seem to have a faster maximal SPV at an earlier time (see Figure 4.3). But only the maximal SPV of the *Doubling* is significantly slower than the *Cross strike - with strength* (t(16) = 3.56; p = <0.001). The time of the maximum SPV is not significantly different for any of the three Strike pairs.

The following describes the SPV in training. Figures 4.4a, 4.5a, 4.6, 4.7, 4.8, 4.9, 4.10 & 4.11 show the mean SPV in red and the standard deviations in black. Figures 4.4b & 4.5b are representative examples of the movements of one fencer and of one repetition.

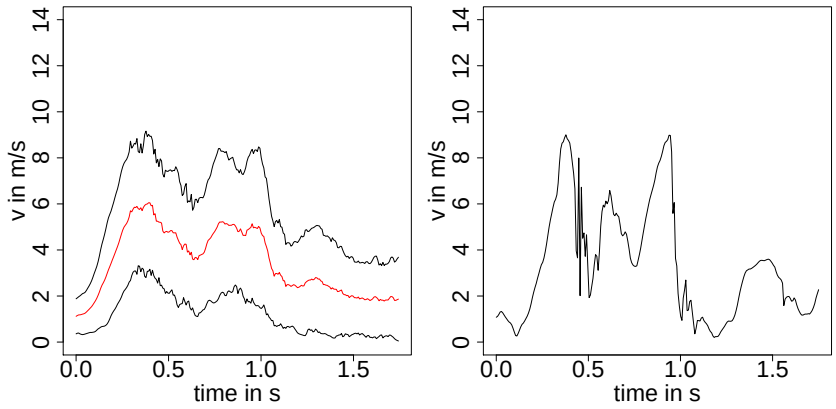
Every technique has at least one SPV maximum. Each maximum stands for one movement phase in the technique.

In Figure 4.4 the SPV of *Taking Off* is illustrated. When looking at the SPV of one repetition three maxima can be spotted (see Figure 4.4b). The first peak is from the first attack. The second velocity maximum at arround 0.60 s is due to pulling the swordpoint over the opponent's swordpoint. And the last peak stands for the last Strike to the head of the opponent after



(a) Mean maximal SPV. (b) Time of the maximal SPV.

Figure 4.3: Technique pairs: *Taking Off* & *Range strike - Taking Off*, *Doubling* & *Cross strike - with strength*, *Changing Through* & *Range strike - Changing Through*.



(a) Mean (red) SPV with standard deviations (black).

(b) VP 5 trial 2.

Figure 4.4: SPV of Taking Off in training.

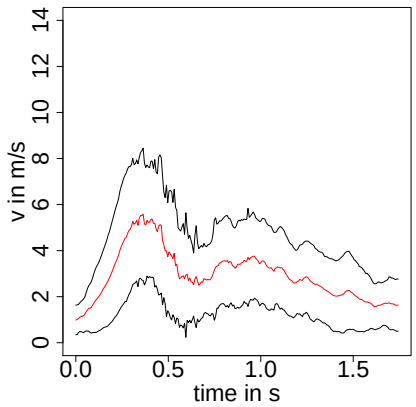
which the technique is over. The *Taking Off* has three maxima. The first phase and the last phase have nearly the same maximal velocity of the swordpoint. The second phase has a slower sword velocity.

These three phases are also visible in Figure 4.4a. But they are not as obvious as for the individual technique. The mean standard deviation of the SPV of *Taking Off* is 2.05 $\frac{m}{s}$. This explains the less apparent maxima.

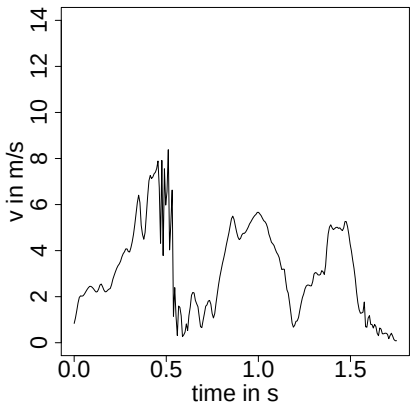
The SPV of *Changing Through* is shown in Figure 4.5. The individuall SPV (see Figure 4.5b) shows three velocity maxima like *Taking Off*. The first peak is due to the attacking of the opponent. The second velocity maximum comes from changing the sword point through below the opponents sword. The third movement phase, which is also seen in the sword velocity, is from the hit towards the opponent. The first phase is the fastest. The other two phases have nearly the same velocity.

The mean SPV of *Changing Through* (see Figure 4.5a) only has two SPV maxima. With a mean standard deviation of 1.84 $\frac{m}{s}$ the loss of one maximum can be explained.

Figure 4.6a shows the mean SPV during *Doubling*. This technique has two movement phases. The first phase which takes place in the first 400 ms is the attacking phase. In the second phase the hitting of the opponent is performed. The mean standard deviation is 2.11 $\frac{m}{s}$.



(a) Mean (red) SPV with standard deviations (black).



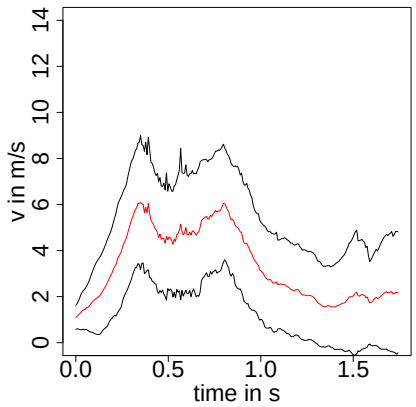
(b) VP 1 trial 5.

Figure 4.5: SPV of Changing Through in training.

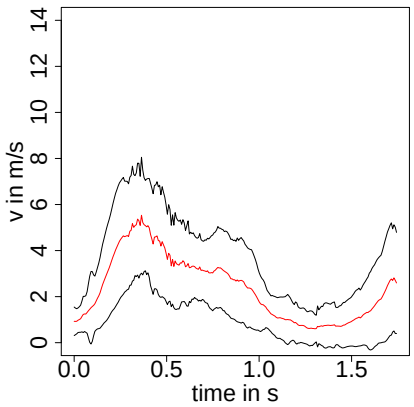
In Figure 4.6b, the SPV of *Mutating* is drawn. The Strike has a clear first movement phase which represents the first attack of the opponent. Between 750 ms and 850 ms a smaller velocity maximum than in the first phase is pictured. This is due to the thrust which is performed in attacking the opponent. The mean standard deviation is 1.66 $\frac{m}{s}$.

From the velocity it can also be seen that *Mutating* has a shorter duration then *Doubling*. The two Principles have two movement phases.

As shown in Figure 4.7a, *Following After* has one SPV max-

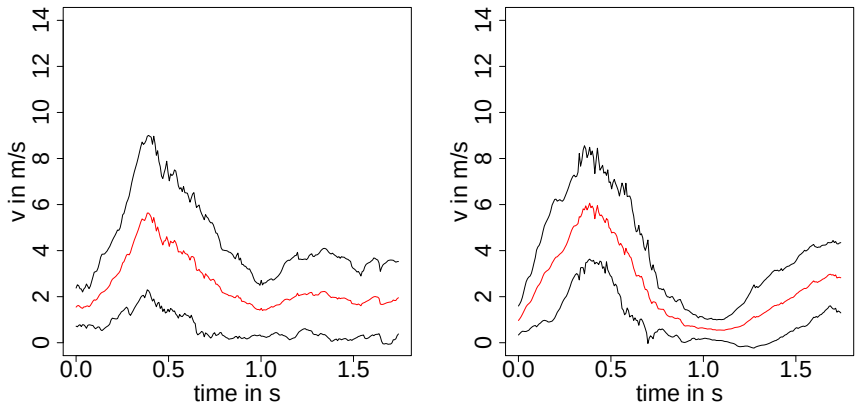


(a) Doubling.



(b) Mutating.

Figure 4.6: Mean (red) SPV with standard deviations (black).



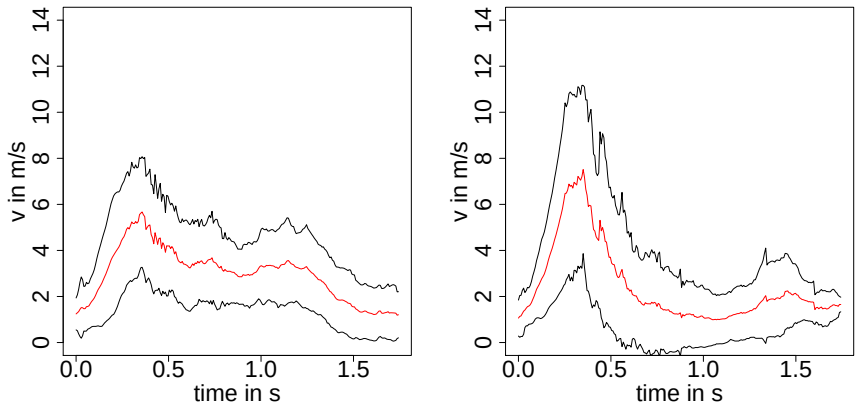
(a) Following After. (b) Setting Off.

Figure 4.7: Mean (red) SPV with standard deviations (black).

imum arround 400 ms which stands for one movement phase. This phase comes from the one hit which is performed to attack the opponent. The mean standard deviation is 1.70 $\frac{m}{s}$.

Similiar to *Following After* is the *Setting Off* which can be seen in Figure 4.7b. This Principle has also a maximal SPV at arround 400 ms. This results from the one attack which is made to hit the opponent. The mean standard deviation is 1.39 $\frac{m}{s}$.

Twitching (see Figure 4.8a) has three SPV maxima like *Taking Off* and *Changing Through*. But in this case the three motion phases are not that clear. The first Strike is the attack. It is



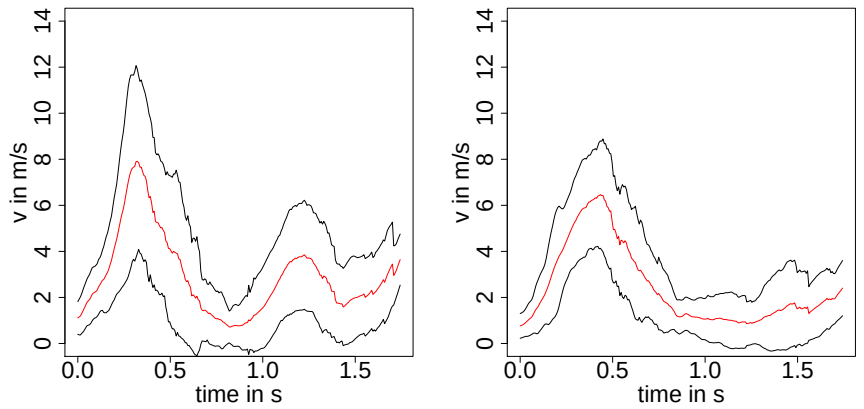
(a) Twitching.

(b) Range strike - against Upper strike.

Figure 4.8: Mean (red) SPV with standard deviations (black).

followed by pulling back the sword, at 750 ms and thrust to the opponent at 1200 ms. The mean standard deviation is 1.56 $\frac{m}{s}$.

In Figure 4.8b the SPV of the *Range strike - against Upper strike* is drawn. There is one maximum at arround 400 ms when the opponent got a deadly hit. The mean standard deviation is 1.82 $\frac{m}{s}$.



(a) Scalp strike - against the Fool. (b) Squinting strike - against Long Point.

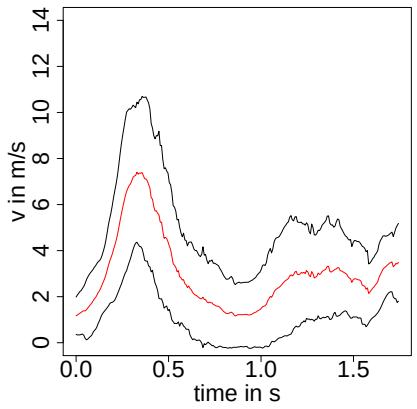
Figure 4.9: Mean (red) SPV with standard deviations (black).

The *Scalp strike - against the Fool* and the *Squinting strike - against Long Point* can be seen in Figure 4.9. They both have one SPV maximum which means they also have one movement phase. The second maximum in Figure 4.9a is not part of the technique. It is from pulling the sword back after the technique.

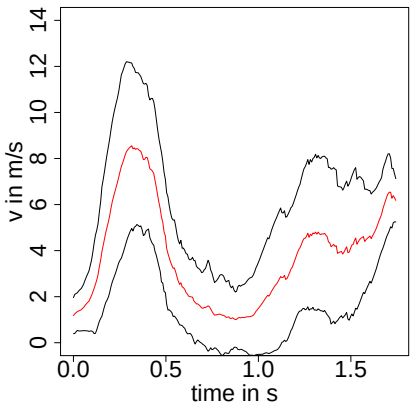
It can also be seen, that the *Scalp strike - against the Fool* has a shorter duration than the *Squinting strike - against Long Point* because the maximum is earlier compared to the *Scalp strike - against the Fool*.

The mean standard deviation of the *Scalp strike - against the Fool* is 1.84 $\frac{m}{s}$ and of the *Squinting strike - against Long Point* is 1.47 $\frac{m}{s}$.

Figure 4.10 illustrates the SPV of the *Cross strike - no reaction* and the *Crooked strike - against Upper strike*. Compared to the *Range strike - against Upper strike*, the *Scalp strike - against the Fool* and the *Squinting strike - against Long Point* they also have one maximum. The increasing velocity after one second is not part



(a) Cross strike - no reaction.



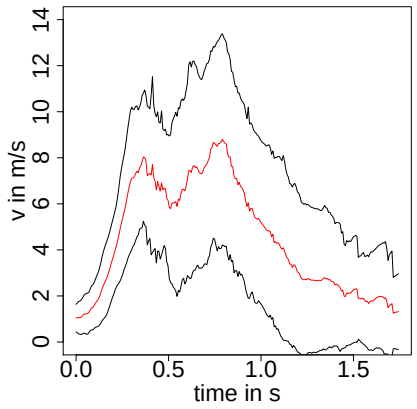
(b) Crooked strike - against Upper strike.

Figure 4.10: Mean (red) SPV with standard deviations (black).

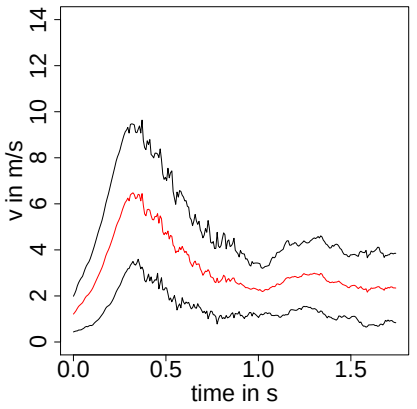
of the technique. It is the same situation as for the *Scalp strike - against the Fool*.

The mean standard deviation for the *Cross strike - no reaction* is 1.98 $\frac{m}{s}$ and for the *Crooked strike - against Upper strike* is 2.30 $\frac{m}{s}$.

In Figure 4.11a, the SPV of *Cross strike - attack the openings* is illustrated. A first velocity peak is reached at around 0.35 s. A second maximum of the velocity is at 0.77 s where the max-



(a) Cross strike - attack the openings.



(b) Scalp strike - against the Crown with Upper.

Figure 4.11: Mean (red) SPV with standard deviations (black).

imal velocity is reached. This maximum is part of the second movement phase. The mean standard deviation is 2.64 $\frac{m}{s}$.

The SVP of the *Scalp strike - against the Crown with Upper* is shown in Figure 4.11b. The start of the movement is comparable to the *Scalp strike - against the Fool*. The rest of the movement can not be divided into multiple phases by the SPV because no further maxima can be recognized. The mean standard deviation is 1.69 $\frac{m}{s}$.

5 DISCUSSION

Previously, the measurement data results for motion comparison, technique and freefight duration and the swordpoint velocity were listed. This chapter includes a discussion about the technique repetitions and the recognition rate of the data processor. The duration of the techniques and the fights are analysed. The swordpoint velocity is looked at. Finally, the DTW costs for training and sparring are interpreted.

5.1 SPARRING RESULTS

When looking at the ranking, two participants stand out. Subject eight who is a novice but takes the first place and subject two who is an expert but takes rank seven.

The division into the two groups was made according to the years of HEMA training and the weekly training duration in hours. This calculation did not take into account the absence in training of the fencers as well as the effort someone puts into the training. When asking the trainer it was clear that subject eight is a very talented fencer who is a beginner when looking at his HEMA age. But when looking at his technique performance participant eight is no novice anymore.

Subject two has a lot of martial arts experience but he is not in training regularly. And he is the only participant who does not prefer the Longsword as a weapon. This is shown in the sparring results.

5.2 TECHNIQUE REPETITIONS

During the freefights 3263 techniques were performed. In total 2143 Guards and 1120 Strikes were made in 119 minutes of fighting. This distribution of Strikes and Guards was to be expected because the watching phase in a fight is normally longer then the attack. This is also normal if the fencers both survive the first exchange of blows.

The expert could name 1598 Guards. This means all other positions which were held when watching the opponents are not described in the ancient sources or the expert was unable to identify them correctly. As described by the expert some Guards were a mixture of two Wards and it was not possible to sort them to one specific Guard. Some participants did a compound of Strikes and Guards, where the Sword was always moving towards the opponent and back again. This kind of behaviour is not described in the sources. Juden et al. (1400) suggest to go through the Guards quickly, which would make the movement back and forth unnecessary.

180 Strikes were definitely identified by the expert. 414 Strikes were recognised as Master Strikes. But the specific Master Strikes could not be detected because the techniques were not performed completely. 526 could not be identified as any known historical strike. Some seem to be mixtures of different strikes but most of these attacks had no similarity to any known attack. Still they were marked as strikes because of the purpose of hitting the opponent and not being defensive, from the experts point of view.

For further analysis in this thesis only the properly identified Strikes and Guards obtained from the expert are investigated to keep the thesis manageable.

5.3 TECHNIQUE RECOGNITION

The recognition rate of the techniques from the freefight can tell if an expert is necessary to annotate the techniques or if the algorithm can do the same. This would mean saving of labour for the expert.

But the algorithm did not have any accordance to the expert if the expert did identify the exact Strike. The algorithm found 45 % of the Guards which is more than chance. But this would also not be sufficient to let the algorithm annotate the Wards.

While the algorithm only has to distinguish the technique performed is a Strike or a Guard the recognition rate is much higher compared to a specific technique. With 69 % hit rate for techniques which were obviously Guards for the expert, a good separation for them is made by the algorithm. This does not

apply to the Principles. They have a high hit rate of 74 % but it is only a random hit for a Strike. This means the algorithm does not recognises if the technique is a Strike or a Guard if the expert clearly identified the technique.

But if the expert could not identify the technique properly the algorithm performs the best for Strikes. It has a 85 % hit rate which is very high in recognising the technique as a Strike. This means that all Strikes have a motion similarity which the algorithm can calculate from movement data.

The unknown Guards can also be detected by the algorithm at 53 % which is also more than the MPHR. But the rate is not as high as it is for the Wards which were recognised by the experts. This supports the experience of the expert who described a back and forth movement in the Wards, which seem more to be like a Strike.

5.4 TECHNIQUE COMPARISON

The lower DTW costs for the Guards compared to the Strikes has been expected. This is the case because Guards are postures and not movements. It would be overkill to analyse the Guards with the DTW algorithm but to compare the results with the Strikes the same method was choosen.

Except for the *Barrier guard* all Wards have DTW costs beneath 0.10. This is the case because the footwork for the *Barrier guard* is not well-defined. For the *Barrier guard - left* it is possible to have the left or the right foot in front. The same applies to the *Barrier guard - right*. This can be seen in higher DTW values of subjects 1 and 6. They mixed the footwork in training. For all other Guards the foot positions are well defined in the sources and are done properly.

The DTW costs are significantly higher in sparring than in training. For the comparison of the training Strikes with the Strike of the freefight no Master Strikes are discussed because they were not recognised properly by the expert. There is a significant difference of the DTW costs between the training and the freefight for the executed Principles *Taking Off*, *Setting Off*, *Changing Through* and *Following After*.

The Guards have a significant difference in the biomechanics of training and sparring. The only exception is the *Barrier guard*. This may be a statistic error because the Guard was only done 12 times during the sparring. Another reason could be that this Ward has more flexible foot positions in training then all other measured Guards. This makes the Guard similar to the freefight because the feet need to work independent from the rest of the body in sparring. This is necessary because the fencers move as freely as possible in the fighting area. Then it is not always possible to keep the proper foot positions for the Guards.

This means that the techniques are performed differently in freefight than in training. This is the case because the subjects did different footwork, had another starting position for the technique or fought 'dirty'. For the Guards footwork is made in sparring which was not made in training.

No significant difference was found between the DTW costs of Strikes and Guards in the freefight. This may be caused by both technique variations include steps and sword movement.

Experts have significantly higher DTW costs for Strikes in training than novices. This means that experts have a large movement variation for one Strike. These variations can be different footwork or variable sword attacks[1]. They are important for the freefight because the opponent does normaly not move as expected. Novices are less adaptive in freefights then experts, which can be seen in the fight results.

For the Guards there is no significant difference of the biomechanics in training between experts and novices. Compared to the Strikes, Guards are less complex and easier to perform. The experience does not affect the performance of the Ward.

5.5 DURATION OF TECHNIQUES

The duration of a technique is affected by different parameters. For Guards the situation in which it is used is very important. Juden et al. (1400) says if you do not move, you are dead, if you move, you are alive. This also means that a fencer should not stay in one Guard very long, so the duration for Wards should

1 different angle or start position of the sword

be short. But they can be even faster if the opponent attacks before changing the Guard.

Strikes can be divided into two types. One type of techniques has only one attacking phase, which is often called *in the Instant*. The other has two attacking phases, where the first action is *in the Instant*, but another attack is following the first one. To make the second movement, an opponent's reaction needs to be made. Depending on the reaction of the opponent, the following motion is different. The corollary is a longer technique duration for the second type of movements than for the first type.

Strikes are also shorter if they are performed faster. A shorter duration is also possible if the technique is interrupted before the end. The same result appears if the technique is not performed from the usual starting position, which usually would happen if a fencer has to react to his opponent's behaviour.

5.5.1 *Training*

At first we look at the technique duration in training. Those techniques are always performed completely, because the subjects were ordered to do the technique as accurately as possible, which was checked by the investigator. The technique duration may be longer because of this instruction.

The *Range strike - against Upper strike* duration is much slower at 1.37 s as compared to Koshida et al. (2011) and Kohutovič (2013) which only had a movement duration of 340 to 350 ms. The techniques of Koshida et al. (2011), Kohutovič (2013) are quite similar to the *Range strike - against Upper strike*. But the duration of Koshida et al. (2011) and Kohutovič (2013) ends at the time the opponent or the aim was hit. Comparing the times with the maximal SPV from this thesis with 420 ms of the *Range strike - against Upper strike* the duration is more alike. But the time of the maximum SPV is earlier than the time of hitting the opponent. The slower movement can be explained by the weight of the weapon. The Shinai[2] has a weight of arround 500 g and a length of 120 cm. Kohutovič (2013) used a Feder[3] with a weight

2 Weapon in Kendo
3 Lighter Longsword

of 1.5 kg and a length of 127 cm. Both weapons are lighter which makes it easier to strike faster.

The *Crooked strike - against upper strike*, *Following After*, the *Scalp strike - against the Fool*, the *Cross strike - no reaction* and the *Range strike - against Upper strike* are the fastest techniques in training with a duration of less than 1.40 s. This result has been expected because these techniques have only one attacking phase.

By contrast, the long durations of the Stikes are unexpected. The only Strike which has a duration which is explainable in comparison to the duration of the other techniques is the *Scalp strike - against the Crown with upper*. With a duration of 2.85 s it is the technique that takes the longest. This technique has two phases. The long movement time is ascribable to the fact that this technique is not trained very often. It is unexpected that the *Changing Through*, the *Range strike - Changing Through* and the *Twitching* also have a duration over two seconds. Each other than the *Scalp strike - against the Crown with upper* these techniques are trained very often and are part of the basic training. By comparing these three techniques with the other techniques which have been measured it stands out that these Strikes have one thing in common. The binding of the swords is changed from the right to the left side. This also happens when the fencer performs the *Taking Off* or the *Range strike - Taking Off* which have a duration of shorter then two seconds. But when the *Taking Off* is executed, the swordpoint is led over the swordpoint of the opponent. When performing the *Changing Through* or *Twitching* the swordpoint is directed next to the cross of the opponent's sword. This movement needs a lot of precision which makes the technique slower than others.

The duration differences of the three different *Crooked strike* variations has been expected when compared to each other. The *Scalp strike - against the Fool* is one of the fastest techniques. The *Scalp strike - against the Crown with Upper* is the slowest technique. Compared to the other Master Strike variations *Crooked strikes*, *Squinting strikes* and *Cross strikes* have the largest duration variations. Only the *Range strikes* have a similar duration range.

It is interesting to see that the similiar pair of techniques *Taking Off* and *Range strike - Taking Off*, *Doubling* and *Cross strike*

- *with strength* and *Changing Trough* and *Range strike - Changing Through* also have an equal duration.

Strikes which only have one phase are all faster than 1.70 s. The slower techniques are more complex and have a second movement phase which nearly always needs a reaction of the opponent first.

5.5.2 *Sparring*

The Strike duration of the training and the freefight is similar. The Strike duration is significantly shorter in sparring than in training. This can be the case because the Strikes were performed faster in the freefights. It is interesting to see that *Following After* is the slowest Strike during sparring though it was the fastest of the five techniques in training. It is possible that the starting position in the fights was different from the starting position in training. The technique may also be interrupted because the opponent made a conter technique to which the fighter had to react.

If the subjects did change through the Guards evenly the duration should not vary. The number of the Guards show a clear preference of the *Plough - left*. It also has a long average duration of 1.72 s. The Wards *Fool - left*, *From the roof - right* and *Plough - right* were also performed very often. But the holding time for the *Fool - left* and the *Plough - right* are shorter (around 1.08 s) than for the *Plough - left* and the *From the roof - right*.

The *Side guard*, the *Ox* and the *Barrier guard* were only done a few times compared to the other Wards. They are not prefered Guards in freefights.

The subjects were asked which Guards they prefer in sparring. All nine fencers said they perform the Wards *Plough*, *From the Roof* and the *Fool*. This could be confirmed by the data that has been measured. In the questionnaire the participants answered that they did *Ox* more often than the *Barrier guard*. Looking at the data it was the other way round.

The same was asked for the Strikes where the *Range strike* was mentioned by eight fencers, the *Cross strike* and *Following After* was marked by seven subjects and *Twitching* and *Setting Off* was ticked by six fighters. It is unknown if the Master Strikes

were performed. The Principle *Setting Off* was performed most often which agrees with the answers of the subjects.

5.6 DURATION OF FIGHT

The duration of the fights equal the duration of the pilot study (Merkert, 2018) (see Table 5.1). This is interesting to see because the fight rules are the same but the fight modes are different. In the pilot study 60 freefights with six subjects were measured. Every participant did 20 fights in a maximum of 70 minutes. The fight order was randomised. In the worst case a fencer had 20 fights in a row, which actually was not the case. In this thesis one fencer had to fight 32 fights in a row. This fighting mode is very stressful for the fighters and it could lead to uncomparable fights and techniques during the measurement.

But as we can see the duration of the fights in this thesis is comparable to the randomised fighting mode of the pilot study. The fencers also said that they felt good during all 32 fights and were surprised how easy they came through the fights. The comparability of the techniques is also possible because all subjects had the same conditions.

Table 5.1: The fight duration in seconds in comparison to the thesis and according to the pilot study (Merkert, 2018).

	Thesis	Pilot study
Mean	24.96	27.53
SD	4.79	3.32
Min	11.08	9.00
Max	54.30	60.00

5.7 MAXIMUM SWORDPOINT VELOCITY

The SPV has only been researched in training because of the technique validity. The maximal averaged SPV of 11.13 $\frac{m}{s}$ is reached after 0.52 s on average.

The different maximal SPV for the techniques are interesting to see. The techniques which include a thrust have the lowest

velocity at 9.10 $\frac{m}{s}$. The highest velocity of 14.09 $\frac{m}{s}$ is reached with the *Cross strike - attack the openings*. Examples of other sports where the athlete holds a piece of sports equipment in his hands are tennis, baseball and golf. Compared to a serve in Tennis with the record velocity of 246 $\frac{km}{h}$ (68.33 $\frac{m}{s}$) by Andy Roddick (Ivančević et al., 2008), the launch speed of a homerun hit in baseball with 50 $\frac{m}{s}$ (Adair, 1995) or a golf ball with a launch speed of 61 $\frac{m}{s}$ (Penner, 2001), the measured velocities are small.

But for the Karate punsh *Gyaku-Zuki* the maximal velocity of the fist was between 7.60 and 9.50 $\frac{m}{s}$ (Hofmann et al., 2008; Hofmann & Witte, 2011). The Karate frontkick *Mawashi-Geri* has a maximal foot velocity between 2.19 and 3.50 $\frac{m}{s}$ (Emmermacher et al., 2007).

Compared to all other Strikes the *Cross strike - attack the openings* reached the maximum SPV 20 to 30 seconds later. This can only be explained by the fact, that the maximal SVP is reached in the second phase of the Strike. This is illustrated in Figure 4.11a.

A similar time of the maximum SPV can only be seen in the *Taking Off* at 0.71 s. For the maximum SPV the global maximum was choosen. This maximum can be in the first as well as in the last phase. This leads to a mean time of 0.71 s for the maximal SPV. But there was no such maximum. The real maxima are around 0.40 s or at 0.95 s.

Liechtenauer et al. (1504-1519) said that when performing a Master Strike, the first Strike should hit the opponent. Falkner et al. (1510) wrote, that if a Master Strike can be blocked by the opponent, the opponent is a Master. This seems to make sense when looking at the SPV for the Master Strikes. Half of the measured Master Strikes have a velocity faster then 11.50 $\frac{m}{s}$. On average all other Strikes are slower.

The idea of the first 'deadly' hit is also illustrated by the SPVs. When looking at the *Range strike - against Upper strike* (Figure 4.8b), the *Scalp strike - against the Fool* (Figure 4.9a), the *Squinting strike - against Long Point* (Figure 4.9b), the *Cross strike - no reaction* (Figure 4.10a) and the *Crooked strike - against Upper strike* Figure 4.10b, they all have only one SPV maximum. This means that after the first strike, the fight would end.

In all SPV figures the velocity increases at the end of the

technique. This is due to the annotation of the data. The end of the technique was annotated when the fencer pulled his sword back towards him. This motion leads to an increasing SPV which can be seen in all velocity drawings.

In some of the SPV figures are velocity measurement errors, which are characterised by high, fast and short peaks (see Figure 4.4b and 4.5b). This kind of measurement noise always occurs when both swords have contact.

The SPV of the techniques are expected. When a technique includes a Thrust and a Strike, it can be seen that the Thrust is slower then the Strike. Though Thrusts are very difficult to block because they come from a blind spot or they come straight to the opponent, it is difficult to estimate the distance.

The SPV of *Doubling* also needs a closer look. It seems that the SPV is higher in the second movement phase, but this is not the case because a measurement error occured as described above. These kinds of errors change the maximal SPV, but this is the reason why the mean was calculated for the analysis.

In Figure 4.8a, which shows *Twitching*, no proper phases are seen. This is the case because when performing this Principle the sword of the opponent and the fencer who does the technique have contact most of the time. And as already said this leads to measurement errors.

The velocity of the swordpoint at the moment when the sword is hitting the opponent is unknown because the point of time can not be validated. But the maximal SPV is not expected to be the hit point. After the maximum, the velocity of the sword does not increase linearly. The gradient changes even more steeply after hitting the opponent.

Individual SPV can become even faster, but the examined average values compensate any measurement errors.

6 CONCLUSION

Untill now no such extensive investigation of HEMA Longsword techniques has been known. Longsword Guards and Strikes were examined in two experimental parts. The technique duration in training and freefight and the fight duration was examined. The technique repetitions in freefight were counted and the swordpoint velocity was calculated.

With this thesis a first step has been made towards the complex analysis of HEMA movements. A lot can be learned from the collected experience and data from this experiment.

Changing through the Guards is as important as to strike fast and react quickly.

The systematic analysis of which techniques were used in the freefight can help to improve the training for sparring. In this study technique duration for multiple techniques were measured. This is a beginning for prospective analysis of the technique duration.

Every technique has its own DTW cost value. It is not known whether there exist previous DTW analyses for Longsword techniques. The measured training data are references for the fight techniques and for future biomechanical analysis.

For the fight duration it is not important if the fencer fights 32 fights in a row or not. But the challenge of the huge amount of fights in a row is a mental dare. To train the necessary mental strength for fighting, the row fights are a good training method. It is important to keep the true aim in mind: always survive. But to fullfil this aim, the technique execution is neglected.

It is a fact that training the ancient techniques improves the ability of sword handling which leads to fast Strikes and reactions in the fight. If the technique execution of techniques described in sources is important to win a fight the training should be structured as follows (Gyarmati, 2016):

1. A good and variable footwork is basic knowledge for good fencing

2. Techniques are made slow from a short distance, the opponent is cooperative and both fencers know which technique is performed
3. Techniques are made fast from a short distance, the opponent is cooperative and both fencers know which technique is performed
4. Techniques are made slow from a long distance which makes variable footwork necessary, the opponent is cooperative and both fencers know which technique is performed
5. Techniques are made fast from a long distance, the opponent is cooperative and both fencers know which technique is performed
6. Techniques are made slow from a long distance, only the attacking fencer knows which technique is performed, the other fencer needs to react to the attack
7. Techniques are made fast from a long distance, only the attacking fencer knows which technique is performed, the other fencer needs to react to the attack
8. Sparring

Those eight steps need to be repeated over and over again. Beside the technical skills dexterity, agility and adaptivity are the keys to win in freefights. This is due to the short fight duration and the opponent's Strikes. Especially the Strikes vary quickly, though a proper reaction is necessary to survive the fight. Physical and mental strength is important to be successful in HEMA as a fencer.

The more a fencer goes into sparring the more experience he gets. This is what he needs to get better.

Techniques are performed differently in freefight than in training. This leads to the assumption, that historical techniques are not useful and usable in a freefight situation. But looking at the measured data, there is a lot more to examine to definitively put an end to this discussion.

7 FUTURE WORK

To get results for the intraindividual analysis the techniques of training should be measured twice. The same can be done for the fights.

It would also be better to have more participants. But if we took into account a larger number of subjects and more technique repetitions and fights the effort would be enormous. With the setting described here the measurement time for every participant was arround 16 hours. If the subject number stays the same but the training and sparring sessions are made twice a measurement duration of 32 hours per subject can be expected. For every additional participant, who is measured, at least three hours must be added for the time investment. When 12 fencers are investigated, this would lead to 41 hours per subject.

But not only the fencers' time is needed. It took 16 hours to annotate the data of one participant by one expert for this thesis. If the measurement duration is twice as long 32 hours would be needed for every subject. This leads to a total annotation time of 384 hours for 12 fencers for one expert. This would mean, if the expert annotated the data eight hours per day, five days per week, he would need more then two months for data annotation.

Less is known about the Master Strikes from this analysis. Because of its complexity the Master Strikes were not investigated further in this thesis. To analyse the Master Strikes the Weight-Optimized Open-End Dynamic Time Warping (WOOE-DTW) (Hülsmann et al., 2017) would be necessary. In this analysis the technique does not need to be complete. This would also make sense for the Principles in freefight. For the training this kind of analysis does not make sense because all techniques are performed from start to end.

To get better recognition rates, which would replace the expert, the motion data could be weighted or other classification algorithms could be used. This way it could also be found out which body parts play the most important roles for a specific technique. When we know what body segments let us know which technique is performed, the fighters can train to look at

these segments of the opponent. This knowledge gives an advantage to the fencer. With this analysis the focus can be put on the upper body. This makes sense because the steps are supposed to work independently from the technique. The upper body has a more important role in the technique performance then the legs.

A more detailed annotation leads to more information about the technique like the duration from the first sword movement till the opponent gets hit. It is also possible to compare movement primitives of different techniques.

For future measurements in this area it could be helpfull to measure the Guards in training with footwork. This could lead to no significant differences between the Wards in training and in Fight.

Randomising the order of the sparring would make more fights in one row possible. To do that every fencer needs to be equipped with 16 sensors. For 12 participants this would make 192 sensors necessary. Regardless of the number of sensors it would be interesting to measure both fighting subjects. This would lead to a larger set of techniques and the actual interaction of both fighters can be taken into account.

It may also be interesting to compare if the technique duration differs significantly for novices and experts. To compare the technique duration in training and freefight or different training levels, it is necessary to know if the technique was used completely or not. This information is missing in the current study. But with more time the technique completeness can be found out because of the two sided high speed video recordings.

When it is known whether the technique was made completely in freefight the SPV can also be analysed properly in there. If other experts annotate the techniques and add the completeness for every technique it is also possible to add the annotation for the time of the opponent hits. But this is also different because from a 2D Video it is sometimes impossible to see if the fencers hit each other or not. It may be necessary to add other measurement methods as for example in Olympic fencing.

It is unknown if the hitrate increases with a better technique execution. To evaluate this it would be necessary to define if the hit technique was just any sword movement or a technique described. When this question is answered it can be ask if the

trained techniques are required to increase the chance of winning a fight.

These points seem to be worth investigating in the future. With this thesis a first step in movement analysis in HEMA has been made. But only the surface of the system was scratched.

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APPENDIX INTRODUCTION

In this part additional data tables are shown in Chapter B. In the Chapters C Guards, D Principles and E Master strikes you can find a short technique description from the HEMA GLOSSAR site. In Chapter F the used questionnaire can be seen.

ADDITIONAL TABLES

B

Table B.1: Mean and SD of technique duration (in s) and number of repetitions of Principles and Guards during Sparring for all participants; C = Count.

VP	1		2		3		4		5		6		7		8		9	
Strikes	Mean SD	C	Mean SD	C	Mean SD	C	Mean SD	C	Mean SD	C	Mean SD	C	Mean SD	C	Mean SD	C	Mean SD	C
Taking Off	0.99 0.06	3			0.83 0.22	3	1.37 0.04	3	0.75 0.15	2								
Setting Off	1.15 0.61	5	1.01 0.25	7	0.94 0.34	11	1.22 0.35	11	1.15 0.15	8	1.14 0.43	11	1.25 0.66	18	1.40 0.59	10		
Changing Through	1.15 0.93	3	1.51	1	0.60 0.37	52	0.74 0.22	2	1.05 0.21	3			1.06 0.83	2				
Mutating	1.07 0.64	4											2.15	1				
Following After	0.90	1	1.06 0.14	2	1.22 0.44	6	1.06 0.24	2	1.16	1			1.21	1	1.97	1	0.75	1
Fool – left	0.60 0.98	3	1.68 1.37	61	1.43 1.38	39	1.07 2.25	47	0.52 0.39	30	0.71 0.48	8	0.96 1.04	6	0.82 0.73	3	2.07	1
Fool – right			0.97 0.99	15	0.63 0.68	8	0.66 0.76	9	1.66 1.87	6	0.69 0.55	3	1.83 2.20	4	0.36 0.28	3	0.50	1
Side guard – right					0.40	1												
Ox – left	0.21	1	1.12 0.23	5	1.37 2.36	12	0.60 0.37	4	0.45	1	0.09	1	1.00 1.28	8				
Ox – right			0.96	1														
Plough – left	1.76 1.95	75	1.33 1.03	61	1.66 1.81	128	1.15 0.91	56	0.49 0.25	2	3.09 2.78	16	1.80 2.07	81	2.26 1.63	30	1.98 1.58	125
Plough – right	0.37	1	1.01 1.35	5	0.77 0.48	30	0.93 0.87	9	1.25 1.08	3	2.28 1.38	5	0.66 0.59	7	1.20 1.23	19	1.09 0.52	68
Barrier guard – left	1.46 2.56	5	2.84	1	3.00 2.21	3							1.23 1.35	2	0.98	1		
Barrier guard – right			0.91 0.19	2	2.98 2.62	12	1.64 1.63	37	0.46 0.34	5					1.62 0.50	2		
From the roof – left													2.19 1.76	66				
From the roof – right	0.98 0.88	6	1.08 1.08	9	2.25 2.25	83	1.50 1.51	42	0.85 1.10	39			3.94	1				

Table B.2: Mean and SD of velocity (in $\frac{m}{s}$) and duration (in s) of Principles and Master Strikes during training session over all participants; MV = maximal velocity.

Strikes	**Duration**		**Time of MV**		**MV**	
	Mean	SD	Mean	SD	Mean	SD
Taking Off	1.89	0.41	0.71	0.18	11.18	1.73
Setting Off	1.69	0.22	0.49	0.10	10.09	1.85
Doubling	1.92	0.26	0.67	0.21	10.47	0.89
Changing Through	2.62	0.50	0.58	0.21	10.07	1.69
Crooked strike – against upper strike	1.40	0.20	0.53	0.27	10.95	2.10
Crooked strike – on hands	1.66	0.27	0.44	0.09	12.77	3.30
Crooked strike – feint	1.79	0.37	0.37	0.08	12.10	2.68
Mutating	1.88	0.17	0.54	0.24	9.20	1.18
Following After	1.34	0.35	0.51	0.09	10.10	1.74
Scalp strike – against the Fool	1.37	0.20	0.42	0.10	11.89	2.04
Scalp strike – against the Crown with Upper	2.85	0.44	0.56	0.28	11.36	0.57
Squinting strike – against Long Point	1.69	0.25	0.49	0.09	9.05	1.86
Squinting strike – to hands against Upper strike	1.57	0.22	0.45	0.10	10.55	1.87
Cross strike – no reaction	1.40	0.23	0.46	0.21	10.91	2.05
Cross strike – with strength	1.92	0.29	0.58	0.16	11.91	0.82
Cross strike – attack the openings	1.82	0.32	0.77	0.21	14.09	1.80
Range strike – against Upper strike	1.37	0.24	0.42	0.12	12.81	2.52
Range strike – Wrath Thrust	1.76	0.38	0.41	0.07	11.37	1.83
Range strike – Taking Off	1.79	0.25	0.58	0.14	12.18	1.52
Range strike – Changing Through	2.63	0.50	0.51	0.11	11.30	2.56
Twitching	2.20	0.57	0.51	0.17	9.28	0.99
mean	1.84		0.52		11.13	

Table B.3: Mean, SD and Minimum of DTW costs for Strikes in training for every participant.

VP	1		2		3		4		5		6		7		8		9		all
Strikes	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD
Taking Off	0.17 0.10	0.14	0.10 0.04	0.08	0.08 0.06	0.06	0.06 0.02	0.05	0.07 0.02	0.06	0.07 0.04	0.06	0.22 0.22	0.19	0.05 0.02	0.04	0.06 0.02	0.05	0.10 0.06
Setting Off	0.10 0.04	0.09	0.08 0.02	0.07	0.08 0.02	0.06	0.06 0.01	0.05	0.06 0.02	0.05	0.08 0.02	0.07	0.09 0.02	0.07	0.05 0.02	0.04	0.12 0.08	0.10	0.08 0.02
Doubling	0.08 0.01	0.06	0.07 0.02	0.06	0.09 0.03	0.07	0.06 0.02	0.05	0.25 0.13	0.21	0.06 0.02	0.05	0.12 0.04	0.10	0.04 0.02	0.03	0.06 0.03	0.05	0.09 0.06
Changing Through	0.09 0.01	0.07	0.12 0.07	0.10	0.11 0.04	0.09	0.05 0.00	0.04	0.17 0.14	0.14	0.09 0.05	0.08	0.12 0.07	0.10	0.07 0.03	0.06	0.05 0.02	0.04	0.10 0.04
Crooked strike – against upper strike	0.06 0.02	0.05	0.07 0.03	0.06	0.07 0.03	0.06	0.05 0.02	0.04	0.07 0.01	0.06	0.06 0.02	0.05	0.07 0.01	0.06	0.05 0.01	0.04	0.08 0.03	0.07	0.06 0.01
Crooked strike – on hands	0.06 0.03	0.05	0.14 0.05	0.12	0.14 0.13	0.12	0.08 0.02	0.07	0.07 0.02	0.06	0.09 0.05	0.08	0.20 0.12	0.16	0.07 0.01	0.06	0.07 0.01	0.06	0.10 0.05
Crooked strike – feint	0.08 0.01	0.06	0.18 0.08	0.15	0.13 0.04	0.11	0.09 0.09	0.07	0.10 0.03	0.08	0.12 0.09	0.10	0.16 0.06	0.13	0.10 0.01	0.09	0.09 0.04	0.08	0.12 0.03
Mutating	0.09 0.03	0.07	0.10 0.03	0.08	0.06 0.04	0.05	0.06 0.03	0.05	0.18 0.07	0.15	0.07 0.03	0.06	0.13 0.04	0.11	0.08 0.02	0.07	0.05 0.01	0.05	0.09 0.04
Following After	0.14 0.12	0.12	0.10 0.03	0.08	0.12 0.07	0.10	0.09 0.01	0.07	0.09 0.05	0.07	0.09 0.02	0.07	0.11 0.05	0.10	0.07 0.03	0.05	0.08 0.04	0.06	0.10 0.02
Scalp strike – against the Fool	0.09 0.05	0.08	0.08 0.02	0.07	0.09 0.06	0.07	0.06 0.02	0.05	0.05 0.02	0.04	0.05 0.02	0.04	0.10 0.02	0.08	0.05 0.03	0.05	0.09 0.02	0.07	0.07 0.02
Scalp strike – against the Crown with Upper	0.14 0.02	0.12	0.16 0.04	0.13	0.09 0.02	0.08	0.08 0.04	0.06	0.15 0.10	0.12	0.12 0.05	0.10	0.14 0.04	0.11	0.12 0.05	0.10	0.07 0.03	0.06	0.12 0.03
Squinting strike – against Long Point	0.06 0.02	0.05	0.12 0.03	0.10	0.09 0.05	0.07	0.04 0.01	0.03	0.08 0.03	0.07	0.07 0.02	0.06	0.11 0.04	0.09	0.07 0.02	0.06	0.05 0.01	0.04	0.08 0.03
Squinting strike – to hands against Upper strike	0.08 0.02	0.07	0.06 0.02	0.05	0.08 0.02	0.07	0.09 0.06	0.08	0.07 0.03	0.06	0.09 0.02	0.08	0.10 0.02	0.08	0.08 0.05	0.07	0.07 0.04	0.06	0.08 0.01
Cross strike – no reaction	0.06 0.02	0.05	0.09 0.02	0.07	0.07 0.02	0.06	0.07 0.02	0.06	0.07 0.03	0.06	0.09 0.02	0.07	0.14 0.04	0.12	0.07 0.02	0.06	0.06 0.01	0.05	0.08 0.02
Cross strike – with strength	0.06 0.01	0.05	0.11 0.06	0.09	0.11 0.04	0.09	0.06 0.01	0.05	0.07 0.03	0.06	0.09 0.03	0.07	0.12 0.06	0.10	0.05 0.02	0.05	0.10 0.04	0.08	0.09 0.02
Cross strike – attack the openings	0.10 0.03	0.08	0.11 0.03	0.09	0.11 0.07	0.09	0.07 0.02	0.06	0.10 0.03	0.08	0.07 0.02	0.06	0.11 0.06	0.09	0.06 0.02	0.05	0.08 0.03	0.07	0.09 0.02
Range strike – against Upper strike	0.10 0.03	0.08	0.14 0.06	0.12	0.13 0.05	0.11	0.05 0.01	0.04	0.07 0.02	0.06	0.08 0.02	0.06	0.09 0.03	0.07	0.07 0.04	0.06	0.06 0.02	0.05	0.09 0.03
Range strike – Wrath Thrust	0.10 0.03	0.08	0.10 0.06	0.09	0.12 0.03	0.10	0.04 0.02	0.04	0.09 0.05	0.07	0.06 0.01	0.05	0.11 0.08	0.09	0.13 0.02	0.10	0.05 0.02	0.04	0.09 0.03
Range strike – Taking Off	0.11 0.03	0.09	0.13 0.04	0.11	0.08 0.02	0.07	0.10 0.04	0.08	0.10 0.01	0.09	0.07 0.02	0.05	0.24 0.12	0.20	0.08 0.04	0.07	0.07 0.02	0.05	0.11 0.05
Range strike – Changing Through	0.10 0.06	0.09	0.41 0.34	0.34	0.15 0.14	0.13	0.08 0.05	0.06	0.09 0.02	0.08	0.11 0.03	0.09	0.08 0.02	0.07	0.09 0.04	0.08	0.11 0.03	0.09	0.14 0.11
Twitching	0.11 0.04	0.09	0.16 0.05	0.13	0.21 0.13	0.18	0.07 0.03	0.06	0.08 0.05	0.07	0.12 0.08	0.10	0.14 0.09	0.12	0.22 0.30	0.18	0.07 0.04	0.06	0.13 0.06

Table B.4: Mean, SD and Minimum of DTW costs for Guards in training for every participant.

VP	1		2		3		4		5		6		7		8		9		all
Guards	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD	Min	Mean SD
Fool – left	0.09 0.06	0.08	0.10 0.04	0.02	0.06 0.02	0.05	0.05 0.07	0.04	0.05 0.03	0.04	0.03 0.01	0.03	0.01 0.01	0.01	0.03 0.02	0.02	0.03 0.01	0.03	0.04 0.02
Fool – right	0.08 0.05	0.07	0.08 0.02	0.03	0.03 0.01	0.03	0.03 0.03	0.03	0.06 0.03	0.05	0.04 0.03	0.03	0.02 0.01	0.02	0.02 0.02	0.02	0.02 0.01	0.02	0.04 0.02
Side guard – left	0.09 0.04	0.08	0.07 0.02	0.03	0.04 0.03	0.04	0.02 0.01	0.02	0.04 0.02	0.03	0.08 0.10	0.07	0.02 0.01	0.02	0.02 0.01	0.02	0.03 0.02	0.02	0.04 0.03
Side guard – right	0.06 0.02	0.05	0.12 0.07	0.04	0.03 0.02	0.03	0.03 0.02	0.03	0.03 0.01	0.02	0.03 0.01	0.03	0.03 0.01	0.02	0.03 0.02	0.02	0.02 0.00	0.02	0.03 0.01
Ox – left	0.07 0.05	0.06	0.07 0.03	0.04	0.03 0.00	0.02	0.03 0.01	0.02	0.03 0.02	0.03	0.06 0.03	0.05	0.02 0.01	0.02	0.02 0.01	0.02	0.02 0.01	0.02	0.04 0.02
Ox – right	0.12 0.10	0.10	0.14 0.05	0.07	0.06 0.04	0.05	0.02 0.01	0.02	0.02 0.01	0.01	0.02 0.01	0.02	0.03 0.01	0.02	0.02 0.01	0.01	0.09 0.08	0.08	0.05 0.04
Plough – left	0.05 0.03	0.04	0.18 0.08	0.03	0.03 0.00	0.03	0.03 0.01	0.02	0.02 0.01	0.02	0.03 0.01	0.02	0.02 0.02	0.02	0.02 0.01	0.02	0.03 0.01	0.02	0.03 0.01
Plough – right	0.05 0.03	0.04	0.10 0.03	0.04	0.03 0.02	0.02	0.02 0.01	0.01	0.02 0.01	0.02	0.05 0.05	0.04	0.03 0.02	0.03	0.02 0.01	0.01	0.04 0.03	0.03	0.03 0.01
Barrier guard – left	0.51 0.98	0.42	0.10 0.03	0.04	0.05 0.04	0.04	0.02 0.01	0.01	0.04 0.02	0.03	0.13 0.20	0.11	0.02 0.01	0.01	0.02 0.02	0.02	0.03 0.02	0.02	0.10 0.16
Barrier guard – right	0.87 1.14	0.72	0.08 0.02	0.03	0.04 0.01	0.03	0.03 0.04	0.03	0.06 0.03	0.05	0.23 0.25	0.19	0.02 0.01	0.02	0.03 0.02	0.03	0.05 0.05	0.04	0.15 0.28
From the roof – left	0.06 0.02	0.05	0.16 0.04	0.08	0.03 0.03	0.02	0.02 0.00	0.01	0.04 0.02	0.03	0.13 0.18	0.11	0.03 0.01	0.02	0.02 0.01	0.02	0.02 0.01	0.01	0.05 0.04
From the roof – right	0.12 0.08	0.10	0.12 0.03	0.13	0.03 0.02	0.03	0.03 0.01	0.02	0.05 0.05	0.04	0.10 0.04	0.08	0.02 0.01	0.02	0.02 0.01	0.02	0.02 0.02	0.02	0.06 0.05

Table B.5: Mean and SD of DTW costs for Strikes and Wards in Sparring for every participant.

VP	**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**		**9**		**all**	
Technique	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Taking Off	0.75	0.01	1.32	0.33	1.03	0.41	0.95	0.34	1.16	0.11									0.97	0.18
Setting Off	1.06	0.30	0.60	0.26	0.67	0.22	1.27	0.28	1.30	0.29	1.32	0.30	1.30	0.37	1.21	0.28			1.18	0.22
Changing Through	1.24	0.40			0.93	0.26	0.85	0.22	1.45	0.29			1.53	0.08					1.20	0.30
Mutating	1.25	0.20																	1.25	0.20
Following After			1.18	0.62	0.67	0.19	0.67	0.06											0.84	0.29
Twitching							0.80	0.37											0.80	0.37
Fool – left	0.67	0.20	0.94	0.32	0.88	0.28	0.64	0.31	0.70	0.30	0.79	0.34	0.75	0.38	0.94	0.45			0.75	0.12
Fool – right					0.93	0.61	0.70	0.43	1.07	0.32	1.46	0.22	0.75	0.39	0.70	0.07			0.94	0.27
Ox – left			1.11	0.15	0.53	0.18	1.26	0.36					1.17	0.38					1.02	0.33
Plough – left	0.88	0.33	1.21	0.31	0.95	0.27	0.66	0.25	0.73	0.02	0.98	0.31	0.95	0.35	0.77	0.24	0.59	0.29	0.86	0.19
Plough – right			1.06	0.45	0.74	0.18	1.21	0.30	1.12	0.21	0.80	0.41	0.46	0.18	0.53	0.27	0.60	0.26	0.81	0.28
Barrier guard – left	1.47	0.43			1.92	0.52							1.18	0.56	1.04	0.05			1.53	0.37
Barrier guard – right			1.49	0.02	2.14	0.47	0.52	0.14	0.98	0.32									1.23	0.61
From the roof – left	0.95	0.39	0.96	0.38															0.96	0.01
From the roof – right	0.84	0.30	1.13	0.39	1.27	0.35	0.78	0.34	0.74	0.35	0.84	0.27	0.71	0.34	0.62	0.24	0.64	0.31	0.84	0.22

Table B.6: Proportions of the subjects in cm.

VP	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Inion to C7	13	10	11	11	11	14	11	12	9
C7 to T10	26	22	25	27	29	25	27	30	28
T10 to S2	24	37	34	30	28	30	24	27	31
S2 to knee	49	55	49	49	51	53	55	46	52
Knee to ankle	48	49	46	46	51	46	45	51	49
Ankle to toe	27	29	25	26	27	27	25	29	29
T10 to shoulder	26	29	33	29	33	28	22	35	27
Shoulder to elbow	31	37	26	32	32	34	29	32	34
Elbow to wrist	28	29	26	26	28	27	26	32	26
Wrist to middle-hand	6	6	6.5	7	7	7	7	7	6

GUARDS

C

Guards, Wards or Leger is a basic or starting position in medieval fencing. In earlier fencing books, four Guards are mentioned: Ox, Plough, Fool and From the roof. In later sources more Guards are named. The concept of guards is related to the saying 'be on the watch'. Most common Guards are named in Table C.1. Six of them were measured in this study. They are marked with a checkmark.

Table C.1: List of Longsword Guards in English and German and whether used in this thesis.

Ward (english)	Ward (german)	Included
Fool	Alber	✓
From the roof	Vom Tag	✓
Ox	Ochs	✓
Plough	Pflug	✓
Side guard	Nebenhut	✓
Barrier guard	Schrankhut	✓
Speaking window / Long point	Sprechfenster / Langort	
Unicorn	Einhorn	
Hanging point	Hängetort	
Key	Schlüssel	
Rage guard	Zornhut	

C.1 FOOL

A Longsword guard, in which the sword is held straight forward and the point is directed to the ground. It is a defensive ward and pretends to be a 'foolish' guard (see Figure C.1).

C.2 FROM THE ROOF

A Longsword ward, in which the sword is held to the side or above the head. The point is directed upwards or diagonally backwards (see Figure C.2).

C.3 OX

A Longsword ward, in which the sword is held to the side or in front of the head. The point is directed toward the opponent's face like the horns of an ox (see Figure C.3).

C.4 PLOUGH

A Longsword guard, in which the sword is held to the side the hip and the point is directed toward the opponent's face, like the position in plowing (see Figure C.4).

C.5 SIDE GUARD

In the sources, an unclear Longsword guard, in which the sword is held laterally with the point directed down and backwards (see Figure C.5).

C.6 BARRIER GUARD

A Longsword guard, in which the sword is held to the side and in front of the body. The point is directed towards the ground. The sword builds a kind of barrier and it is the prefered starting position for Crooked strike (see Figure C.6).

Figure C.1: Fool left and right side.

Figure C.2: From the Roof left and right side.

Figure C.3: Ox left and right side.

Figure C.4: Plough left and right side.

Figure C.5: Side guard left and right side.

Figure C.6: Barrier guard left and right side.

PRINCIPLES

D

The fencing system of Lichtenauer includes a number fencing principles that can be used in a fight. Some of these principles are simple rules to get a particular situation under control, others are complex processes with different gradings. 14 Principles which came in the short-list are named in Table D.1. The seven Principles choosen for this study are checkmarked.

Table D.1: List of Longsword Principles in English and German and if used in this thesis.

Principle (english)	Principle (german)	Included
Taking Off	Abnehmen	✓
Slicing Off and Pressing the Hands	Abschneiden und Hendtrucken	
Setting Off	Absetzen	✓
The Error	Der Fehler	
Doubling	Duplieren	✓
Pass Through	Durchlaufen	
Changing Through	Durchwechseln	✓
Crown	Krone	
Mutating	Mutieren	✓
Following After	Nachreisen	✓
Snapping Around	Umschnappen	
Turning	Winden	
Twitching	Zucken	✓
Overrunning	Überlaufen	

D.1 TAKING OFF

Release from the binding by sliding up with the sword to the opponent's point and then attack straight forward.

D.2 SETTING OFF

Setting Off is a technique in which the attack of the opponent is parried and one's own attack is performed in the Instant. Your own weapon is moved so that the attack of the enemy shifts from its original direction of movement,

or is parried. The sword is winded in the attack of the enemy and stabbed against him.

D.3 DOUBLING

Strike (stitch, cut) out of the binding: Step diagonally in front of and while binding a Cross strike with the short edge on the uncovered head of the opponent fencer (in the Ox), while one's own head is protected by the cross. Possible left and right. Instead of Cross strike a stitch or cut is possible.

D.4 CHANGING THROUGH

A jerky, circular release of the weapon from the binding after being previously approached in the binding with the enemy. And yet your own point is changed through under the opponent's hilt to immediately put a stitch.

D.5 MUTATING

Point the attack direction from the upper to the lower openings. After binding with the strong edge one winds (in its own strong and in the weak of the opponent), the false edge in the bind by pulling up the own arms (in the ox) and change (mutating) with a stitch in the lower openings by sliding down the opponents blade with the own blade.

D.6 FOLLOWING AFTER

The Following After is a very diverse techique. There are two Following After that take place without a binding and another Following After in binding. Following After when he strikes out. The Following After when he wants to strike you but does not score. The Following After in binding. The following after, when you block his strike and he withdraws his sword strike again. Here we only look at the Following After when he does strike you but does not score.

D.7 TWITCHING

A jerky release of the weapon from the band after having previously approached the enemy in the binding. One notices (in the instant), that he remains in the binding, strike or stitch after the other open side. When the opponent thwarts this intention, strike again to the first open.

E

MASTER STRIKES

The term refers to an important concept from Liechtenauer's school and includes five techniques: Rage strike, Crooked strike, Squinting strike, Scalp strike, Cross strike. In later sources often referred to as 'Master strikes'. Eighteen variations of the Master strikes are named in Table E.1. Fourteen of those situations were measured in this study. They are marked with a checkmark.

Table E.1: List of Longsword Master Strike variations and whether used in this thesis.

Master Strike	Variation	Included
Crooked strike	- on hands	✓
	- against upper strike	✓
	- against Ox	
	- feint	✓
Scalp strike	- against the Fool	✓
	- against the crown with stitch	
	- against the crown with Upper strike and Unterhau	✓
Squinting strike	- against Plough	
	- against Long Point	✓
	- to hands against Upper strike	✓
Cross strike	- no reaction	✓
	- with strength	✓
	- if he is weak	
	- attack the oppenings	✓
Range strike	- against Upper strike	✓
	- Wrath Thrust	✓
	- Taking Off	✓
	- Changing Through	✓

E.1 CROOKED STRIKE

A hidden strike in Liechtenauer's school in which the sword is controlled almost horizontally against the opponent's hands or arms. The strike to left is with the strong edge, the strike to the right with the weak edge.

E.2 SCALP STRIKE

A hidden strike in Liechtenauer's school in which the sword is controlled with the strong edge down straight vertically to the head of the opponent. Strike area is the weak of the sword.

E.3 SQUINTING STRIKE

A strike which begins as an upper strike, but then crosses the vertical and meets with the false edge. Also known as hidden strike in Liechtenauer's school. Later referred to as master strike.

E.4 CROSS STRIKE

A horizontally controlled strike, the hilt is rotated with thumb grip around the right hand. Both hands and the hilt lie before and above one's own head. Also known as hidden strike in Liechtenauer's school. Later referred to as master strike.

E.5 RAGE STRIKE

A diagonal strike from the shoulder with the strong edge, also known as hidden strike in Liechtenauer's school, later referred to as master strike.

F

QUESTIONNAIRE

Age:
Sex:
Weight:
Size:
Handedness:
Training age HEMA (in years):
Agerage number of freefights (all weapons) per week:
Average duration of freefights (all weapons) per week in hours:
Technique training (all weapons) per week in hours:
Number of competitions (all weapons) per year:
Competition rules known:
Fencing gear used:

Guards used in freefights:

- □ From the roof
- □ Fool
- □ Ox
- □ Plough
- □ Side guard
- □ Barrier guard
- □ Others:

Techniques used in freefights:

- □ Taking Off
- □ Setting Off
- □ Doubling
- □ Changing Through
- □ Mutating
- □ Following After
- □ Twitching
- □ Crooked strike
- □ Scalp strike
- □ Squinting strike
- □ Cross strike
- □ Range strike
- □ Others:

I have a favorite Guard in freefights:

- □ No
- □ Yes
- □ If yes, which one:

I have a favorite Strike in freefights:

- □ No
- □ Yes
- □ If yes, which one:

My prefered HEMA weapon is:

- □ Wrestling
- □ Dagger
- □ Long Knife
- □ Sword and Buckler
- □ Longsword
- □ Montante
- □ Long Pole
- □ Half Pole
- □ Poleaxe
- □ Others:

I fight defensively in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

I stay in one Guard in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

I fight offensively in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

I use one exact technique in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

I fight agilly in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

I use my own techniques (not from historical sources) in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

I change through all Guards in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

I perform all historical techniques in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

I lurk in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

I use historically documented Strikes in freefights:

Applies fully						Does not apply at all
1	2	3	4	5	6	7

DECLARATION OF AUTHORSHIP

I hereby declare that I have written this Master's thesis independently and that I have created data sets, drawings, sketches and graphic representations on my own. I have not used any other sources than those indicatedd and have marked the parts of the work taken from other works- including te tables and illustrations used - as borrowed in each case, stating the source.

Hiermit erkläre ich, dass ich die vorliegende Masterarbeit selbständig verfasst und gelieferte Datensätze, Zeichnungen, Skizzen und graphische Darstellungen selbständig erstellt habe. Ich habe keine anderen Quellen als die angegebenen benutzt und habe die Stellen der Arbeit, die anderen Werken entnommen sind - einschl. verwendeter Tabellen und Abbildungen - in jedem einzelnen Fall unter Angabe der Quelle als Entlehnung kentlich gemacht.

Bielefeld, the June 3, 2019 Heike Merkert