Cutting Edge: How Bimanual Asymmetrical Haptic Feedback Enhances VR Training for Butchery Skills

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Fig. 1. University of Twente and Dynteq logo

This thesis explores the integration of the non-dominant hand within Virtual Reality (VR) training environments, aiming to improve both the realism and effectiveness of motor skill development. The specific implementation of the non-dominant hand is with an asymmetrical approach, meaning that each hand is performing a different action. Since many motor learning tasks involve this hand asymmetry, it is important to investigate the implementation of the non-dominant hand. The study introduces a novel learning environment that incorporates realistic haptic feedback for both hands, with a particular focus on the non-dominant hand, to improve task realism. The effectiveness of this system is evaluated through a case study involving butchery, where participants interact with the physical model of meat and see the virtual model. This system, along with the inclusion of the non-dominant hand, is evaluated by participants to assess its effectiveness in enhancing the realism and learning experience. The results indicate that the physical and virtual models closely resemble actual meat, with positive feedback from the participants on the realism and functionality. Incorporating the non-dominant hand improves the quality of the training, as students found the experience more realistic and natural compared to using only the dominant hand. The findings suggest that these advances in virtual reality technology can improve the training of asymmetric bimanual motor skills, providing a controlled and immersive learning environment. This research contributes to the field of VR by highlighting the importance of asymmetrical bimanual feedback and its applicability to various professional training contexts, beyond the specific example of butchery.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**.

Additional Key Words and Phrases: VR, Virtual Reality, Haptics, bimanual, motor skill, learning, butcher, butchery

Contents

1 INTRODUCTION

How do you learn a motor skill in a safe and limitless environment? Consider the training of pilots, astronauts, or surgeons; these trainings cannot be done in real life, since people's lives are at stake. You can imagine that a pilot needs to train before flying an actual plane. This learning problem can be tackled using simulations [31]. Another advantage of using simulations is that you can implement feedback, simplify the situation, or scale the situation [10]. The evolution of virtual reality technology has opened up a world of possibilities for engaging, real and fully immersive learning experiences across a multitude of fields [3]. It is proven that VR is an effective tool used for creating realistic learning experiences [57]. Where a VR headset is a good option for providing visual and auditory feedback, it lacks the capability to let users touch and feel the environment realistically. This is where haptic feedback is implemented [47]. With the addition of haptic feedback, it is possible to implement features such as object hardness, weight (force feedback), surface contact, and temperature (tactile feedback)[11]. Haptic feedback is important for creating an even more realistic experience [61] and allows the user to touch and feel the virtual environment to a certain degree.

Motor skill learning is a complex process that involves the acquisition and refinement of movements that require muscle and limb coordination. Motor skills require repeated physical practice of the specific movements involved in the task [82]. Motor skill learning is influenced by factors such as feedback, reinforcement, attention, and motivation [25]. If one would like to learn a certain motor skill, one would benefit from physical practice [48]. Therefore, it seems logical that having haptic feedback would make motor skill training better in VR [24, 29]. In certain situations, it is proven to be very effective, such as when looking at decreasing surgical errors. Haptic feedback is so important for training in VR that without it, surgical errors increase by a factor of three [79].

But, there is a lack of knowledge with regard to using two hands with haptic feedback in a VR learning experience. Many studies either focus on using a single hand in their VR setups [19] or focus on specific bimanual actions such as laparoscopy, a type of surgery [51]. Laparoscopy involves bimanual symmetric actions, in which both hands perform similar tasks. However, there is a notable gap in the literature on bimanual asymmetric haptic feedback, which involves tasks that require each hand to perform different motor tasks simultaneously.

This lack of research is remarkable, since most skilled manual actions are done in a bimanual asymmetric way [28] and because asymmetrical actions are more difficult to perform[74]. If a bimanual task were performed by one hand, it would even fundamentally change the entire task [39].

The goal of this study is to improve the bimanual asymmetric learning experience in VR, by using haptic feedback and using both the dominant and non-dominant hand. Specifically, we evaluate this principle on the use case of butchery.

The butchery use case was chosen because of its simplicity of cognitive skills but complex motor skills and because of the tasks the butcher performs. The butchery task involves cutting straight, equally thick pieces of meat, which is a bimanual asymmetric task. The dominant hand manipulates the knife to cut through the meat, while the non-dominant hand stabilises the meat and guides the knife. This task effectively demonstrates the importance of haptic feedback, as the knife exerts forces on one hand and as the pressure and deformation of the meat must be felt and adjusted for through the other hand.

From this motivation, a **main research question** was formed for the design and testing of a concept. The main research question is formulated as follows:

RQ *How can haptic feedback enhance the learning experience of two-handed tasks in VR simulations for craft professions such as butchery?*

The sub-research questions were later defined in order to divide the main research question into manageable parts. They are defined as follows:

sRQ1 *How can a realistic 3D virtual and physical model be created of meat?*
  sRQ1a *How can the deforming of meat be implemented in both models?*
sRQ2 *How can the non-dominant hand be included in the learning environment?*
sRQ3 *What role does the non-dominant hand play in the interaction with the meat?*

To execute and test the butchery task, a VR setup will be used that includes detailed haptic feedback mechanisms to simulate the physical interaction with the meat. The VR environment will be equipped with a 3D model of the meat that realistically deforms in response to cutting forces. The task will be evaluated with seven different students from a butchery school.

This thesis is organised as follows; it starts with a review of the related work, where the most important literature is highlighted for VR, haptics, learning motor skills, and what the research choices were. This helps set the context for the study. Then, the foundations of the design is laid where the learning goal is explained but also the types of feedback that should be implemented and the flow of the interaction. The design process is then explained in detail, covering the design of the knife, physically, visually, and the programming of the haptics. Then, the design of the physical and visual meat is explained. After that, the evaluation section describes the specific steps taken to carry out the research, including how data was collected and analysed. The results of the study are then presented with supporting data. The discussion section interprets these findings, exploring their meaning and importance. It also mentions the new insights and limitations of the study. Based on this, the future work section suggests possible areas for further research. The thesis concludes by summarising the main findings and their contributions, reflecting on how well the study met its goals, and highlighting the general significance of the work.

2 RELATED WORK

Simulations are widely used to learn different skills. They are used to replace real experiences with guided ones, which means that you can create a similar experience and implement feedback or guidance [41]. Simulation-based learning has already been implemented in various fields, such as the aviation industry (pilot training), military exercises, and medical doctor training [10, 41]. One of the main advantages of simulation-based training is that someone can perform an action without having real-world consequences. You can imagine that a pilot should first train in a simulator because otherwise, in real life, he could crash a plane [20]. Other advantages are that you can generate feedback in the simulation, simplify the situation, scale the situation, introduce controlled systematic variations, or simulate something that does not often occur (i.e., earthquakes) [10]. Although simulations were previously expensive to perform, with the advent of VR, this problem became less of a limitation [20].

For more information on learning in general, see Appendix B.

2.1 Learning in VR

It is reasonable to assume that VR would be an effective tool for simulation-based learning. This is also supported by literature; many researchers found that it is indeed an effective tool for learning. One of the first studies, dating back to 2002, has already proven that VR training improves operating room performance [65].

In fields such as fire safety and surgery, specialized VR applications have been successfully employed for educational purposes in higher institutions [57]. Things such as immersion, motivation, and VR sickness all influence the degree to which someone can learn from VR training [43]. However, it should be noted that more immersion is not always better, as it can distract from the learning task [34].

Complex motor skill training can be conducted effectively using VR [44]. One of the primary benefits of VR is its capacity to manipulate various parameters, including the task's physical properties, which can be adjusted to suit different training needs. This flexibility makes VR particularly valuable for refining specific motor skills. When no haptic input devices are used in VR it presents significant challenges for tasks that require tactile feedback. Integrating haptic feedback is essential to improve the realism and specificity of the training [44].

Jensen et al. [34] conducted an extensive review on the application of VR in education and training. They state that VR training can improve almost every skill, from cognitive to complex motor to affective skills, but in some fields, it still lacks performance. The main lacking factors are VR sickness, a lack of proper software, and the limitations of the head-mounted displays [34].

2.2 Learning with Haptics

One way of improving the VR training experience is with the use of haptics, for example: For early-phase learning of surgical motor skills in VR, it is important to implement haptics [79]. Force feedback is a very important factor in surgical errors; the absence of force feedback during a surgical procedure in VR increases surgical errors by a factor of three against having force feedback for the same task. To some extent, it is possible to substitute force feedback with sounds. However, studies also found that training with haptic feedback is essential because otherwise the real world situation differs too much [79]. Other studies found that haptic feedback improved the learning curve of junior dental students [53] and can also be a good tool for the education of nurses [12, 49] and for the education of industrial skills [56].

Sigrist et al. [68] found that haptics can be used for a multitude of feedback strategies. One of the strategies of motor learning with haptics is called guidance learning. With guidance learning, the learner is guided to follow a certain path to learn the temporal aspects of the task [24]. This strategy can help beginners learn complex tasks easily and safely, while it can also be adjusted to the level of user skill [68].

Another strategy is using error augmentation, which amplifies error-based learning, which is considered an effective learning method to learn motor skills [68].

Other strategies are; applying resistance against the motion performed, to intensify the environmental experience of the task, to reduce forces such as gravity compensation, or to apply vibrotactile feedback [68]. The choice of haptic feedback depends on the task and the user's skill level

The best way to learn motor skills seems to be with multimodal feedback, using visuals, audio, and haptics to provide feedback to the learner [67, 68]. In that case, each modality can have its use. Multimodal feedback can outperform other individual types of feedback.

2.3 Learning bimanual motor skills

Two-handed interaction is often required to learn motor skills, such as playing a musical instrument, performing surgery, or operating a machine. Research by Guiard shows that the vast majority of human manual acts involve two hands in complementary (asymmetric) roles [28]. If a bimanual task were performed by one hand, it would fundamentally change the entire task [39].

In the realm of VR technology, understanding the nuances of bimanual interactions becomes even more pertinent. By integrating insights from research on bimanual motor control, VR developers can create more immersive and effective training simulations. Such simulations can provide learners with opportunities to refine their coordination and dexterity in a controlled and adaptable environment [83].

2.3.1 Learning bimanual motor skills with haptics. We know that there is a lot of research done on different applications of learning skills in VR, as well as on the use of haptics. This section discusses the learning of bimanual motor skills with haptics in VR. Surgeons and dentists work with two hands, and there is much research done in that field. Multiple studies show that the incorporation of bimanual haptic feedback into simulations significantly improves learning outcomes in these professions [16, 17, 21, 32, 55, 81]. These studies focus on learning very fine complex motor skills used in surgeries and a skill that consists mainly of cognitive knowledge.
Jose et al. [36] proposed a system that uses two desktop haptic devices for medical use, where one represents a hand and the other a needle, so a bimanual asymmetrical task. This system shows potential to speed up learning for the particular skill but is not yet tested [36].
A field that also uses bimanual movements in VR for training, is the training of assembly workers in a factory. Oren et al. found that it takes longer to train in VR with the use of bimanual haptics than physically, but the result is better than when trained physically [50]. A similar study by Carlson et al. found that bimanual VR training is as effective as traditional physical training. They found that, with some modifications, it is possible to obtain the same results from both training variants [13].
Another study found that it is possible to create real-time assembly simulations, i.e. car assembly, with bimanual haptic feedback [62]. This approach proves the effectiveness of bimanual haptic feedback, even in larger, multi-object scenarios.

Various research studies have been conducted in the realm of haptics and VR, encompassing a wide range of applications such as medical skills and assembly skills. However, there exists a research gap since studies mainly focus on specific tasks and often requiring much cognitive skills instead of motor skills. Medical studies primarily delve into the acquisition of precise, fine, and complex motor skills, while assembly skills studies focus more on enhancing spatial awareness. Notably, the investigation of bimanual asymmetric haptics in a context where both hands contribute to a motor learning task that relies on sensory perception rather than cognitive knowledge, has not yet been explored. Thus, the objective of this research is to address this gap by creating a virtual learning experience with sufficient fidelity for both hands to learn the asymmetrical task.

2.4 Research choices

In this subsection, we will delve into the choices that were made before this research. We will explore why VR was selected and why butchery serves as the use case. Although a brief explanation will be provided here, more detailed information can be found in the appendices (A, B, C, D).

2.4.1 Butchery. The butchery use case was chosen due to its simplicity of cognitive skills but complex motor skills and the need for different kinds of learning. There are many tasks that a butcher does, but one of them consists of cutting straight, equally thick pieces of meat. The aim is to cut off an equally thick slice of meat from a ribeye. This is a bimanual asymmetric task because the dominant hand cuts with a knife and the non-dominant hand holds the meat and guides the knife (see Figure 2).

The interaction is as follows: The butcher takes a knife and a piece of meat (ribeye or similar). Places his/her non-dominant hand on the side of the meat and puts pressure on it. This is done against the deformation of the meat. If this is not done, the sliced

Fig. 2. An example of how meat is cut with both hands.

meat will have inconsistent thickness. Also, this hand makes it easier to get equal thickness between the sliced pieces and this hand provides feeling when cutting. The dominant hand grabs the knife and starts to cut the meat until completely cut.

This bimanual asymmetric interaction involves a combination of stabilisation and manipulation. One hand acts as a stabiliser, holding an object steady and providing a fixed point of reference, while the other hand performs the main action, such as cutting, shaping, or crafting. This division of labour allows for precise control and coordination, ensuring that the task can be carried out effectively and safely. In this setup, the stabilising hand provides support and stability, preventing the object from moving or shifting during the action. This is essential for tasks that require accuracy and consistency, as any unintentional movement could result in errors or accidents. Meanwhile, the manipulating hand is responsible for executing the primary task. This hand performs the desired action, whether it is cutting, sewing, pottery, or other forms of manipulation. It requires fine motor skills and coordination to perform the action accurately while maintaining control over the object being worked on. These two hands work together to accomplish the task at hand, with each hand playing a distinct but complementary role in the overall process. The described action will be defined as *stabilised asymmetric bimanual manipulation.*

Definition 2.1. *Stabilised asymmetric bimanual manipulation* is a coordinated motor action in which one hand stabilises an object while the other hand performs the primary task, ensuring precision, control, and safety.

This paper focuses on the use-case of a butcher, but there are many other similar tasks such as:

- Metalworking
- Woodworking
- Pottery
- Sewing
- Jewellery making
- Soldering

All these tasks consists of a stabiliser and manipulator hand, similar to the use-case of a butcher.

This butchery learning task can be done in VR and requires the use of haptics because there is a need for force feedback to make a realistic representation of the task. The VR training would also enable for a limitless learning environment where actions can be recorded and analysed, and students can practice without having the dangers of cutting in his hand. In addition, this task requires motor skills and trial and error learning. Learning this task is normally done with real meat and using sharp knives. An expert indicated that this requires intensive supervision and that people can still cut their fingers when taking the exam. Training in VR can be an outcome for creating a safer and endless learning environment. For more information on the butcher and the full interview, see Appendix C and Appendix D.

2.4.2 XR. The use of virtual reality (VR) has been around for decades, but it has become more accessible and immersive in recent years. VR is a technology that creates a fully artificial environment that the user can perceive and interact with. However, VR is not the only way to alter the perception of reality. There are other technologies, such as augmented reality (AR) and mixed reality (MR), that combine virtual and physical elements in different ways. These technologies are collectively known as X Reality (XR), a term that encompasses the diverse spectrum of artificial realities. XR has many applications and implications for various domains of human activity, such as education, entertainment, health, and industry. Extensive background information can be found in Appendix A. We chose to use VR for this project because it is possible to completely occlude the real world. This opens the door to creating content that can fool the mind with illusion techniques such as haptic retargeting and body warping [5] and many other illusions [42]. These techniques can be used to create a better (haptic) experience. These illusions can be used to trick the mind into having more realism than it really is. Also, in VR it is possible to recreate a realistic learning environment that is not possible with other techniques.

One of the challenges of VR is to provide realistic and natural feedback to the user, for example, through the sense of touch. Haptic technology is the field that deals with creating and delivering touch sensations in XR environments. Haptic devices can range from simple handheld controllers to complex wearable exoskeletons. Haptic feedback can enhance the user's immersion, presence, and performance in XR. More information on haptic devices can be found in Appendix A. Haptic devices will be used for this project to create a more realistic experience for both the dominant and non-dominant hand. Where the choice is to go for a desktop haptic device for the dominant hand to cut the meat as realistic as possible, and a real object for the non-dominant hand for holding the meat.

3 FOUNDATIONS

In this section, we lay the foundations for the design and learning experience of this study. First, the learning goal is discussed, followed by the feedback generation for the learning goal. Finally, the interaction flow of the learning experience is discussed.

3.1 Learning goal

The learning task involves two hands, one hand holding a knife to cut the meat by applying pressure while moving it back and forth with as few cutting strokes as possible. Fewer cutting strokes are preferred because that results in fewer lines on the meat. The other hand acts as a stabiliser, holding the meat with a flat hand. This hand helps maintain an even thickness and provides feedback on the cutting motion. It is also used to press against the meat to prevent deformation. In order to achieve this goal, several steps must be taken, all of which are outlined in this and the next chapter.

3.2 Feedback

One of the steps to achieve the learning goal is to provide feedback to the user. In this subsection, we provide a systematic approach on the creation of different types of feedback during the learning experience. The systematic approach consists of three parts; Creating 20 concepts according to the taxonomy on feedback of Postma et al. [54]. These concepts are then tested on feasibility, and the possible concepts are combined for better and more feasible results. Finally, only the relevant concepts for this research are chosen to give feedback to the learner.

First, 20 concepts have been created from a morphological chart. This is done to include as many feedback types as possible to get a very broad spectrum of feedback concepts. All of these concepts are written down in the list below. For every concept, we chose whether it was feasible to implement it or change it so that it is feasible. These choices are also shown in this list. A short description of all the feedback types used can be found in Appendix H, these feedback types are all used from the research by Postma et al. [54].

Concept 1: **Facilitative, Expert-modelling, Realistic visualizations, Fading, Knowledge of performance, Qualitative, Single-error response, External, Correct**

- **Goal:** Provide real-time guidance by showing an overlay of the learner's cut compared to an optimal cut.
- **Implementation:** Use realistic visualizations to display the ideal cut line in the VR environment. This line fades during cutting.
- **Feasibility:** This cutting line is implemented in the learning experience, but without fading since this is too difficult to do.

Concept 2: **Facilitative, Guidance, Placement, Kinesthetic, Bandwidth, Knowledge of performance, Qualitative, Multi-error response, Prescriptive, External, Correct**

- **Goal:** Help the user understand the expert's approach and technique.
- **Implementation:** Guide the knife action, similar to the expert, with haptic feedback along the correct path.
- **Feasibility:** This concept is partly integrated in the learning experience, where if you deviate from the path too much, the knife will be pushed back.

Concept 3: **Non-essential, Delayed terminal feedback, Abstract mapping, Self-selection, Knowledge of results, Quantitative, Multi-error response, Descriptive, What went wrong, External, Erroneous**

- **Goal:** Provide a summary of performance with visual feedback.
- **Implementation:** Show your own knife cut with variations in color of the knife handle to represent the correctness of the cuts. Green to red means good to bad.
- **Feasibility:** This concept is not feasible, colour of knife may be combined with another concept.

Concept 4: **Essential, Expert-modelling, Realistic visualizations, Self selection, Knowledge of performance, Qualitative, Prescriptive, External, Correct**

- **Goal:** Ensure correct cutting technique by mirroring expert actions.
- **Implementation:** Use visual feedback for seeing the expert cutting the meat, so the student can imitate this.
- **Feasibility:** Feasible.

Concept 5: **Facilitative, Concurrent feedback, Loudness, Fading, Knowledge of performance, Quantitative, Multi-error response, Descriptive, What went wrong, External, Erroneous**

- **Goal:** Improve self-assessment through auditory cues.
- **Implementation:** Loudness decreases for incorrect cuts, providing immediate qualitative feedback.
- **Feasibility:** Audio not feasible.

Concept 6: **Facilitative, Concurrent feedback, Spatialization, Bandwidth, Knowledge of performance, Quantitative, Single-error response, Descriptive, What went wrong, External, Correct**

- **Goal:** Provide real-time spatial awareness of the cutting path.
- **Implementation:** Use spatialized sound to indicate proximity to the correct cutting path.
- **Feasibility:** Audio not feasible.

Concept 7: **Non-essential, Immediate terminal feedback, Pitch, Average, Knowledge of results, Quantitative, Multi-error response, Descriptive, What went right, Correct**

- **Goal:** Provide immediate auditory feedback on a good cut.
- **Implementation:** Use pitch changes to indicate accuracy for good cuts.
- **Feasibility:** Audio not feasible.

Concept 8: **Facilitative, Concurrent feedback, Abstract visualizations, Bandwidth, Knowledge of performance, Quantitative, Single-error response, Descriptive, What went right, Internal, Correct**

- **Goal:** Provide immediate visual feedback on cutting pressure.
- **Implementation:** Use abstract visualizations to indicate if the pressure applied is correct or incorrect.
- **Feasibility:** May be feasible, also dependent on too much information.

Concept 9: **Facilitative, Concurrent feedback, Intensity, Bandwidth, Knowledge of performance, Quantitative, Single-error response, Descriptive, What went wrong, Internal, Correct**

- **Goal:** Improve cutting speed with haptic intensity.
- **Implementation:** Provide intensity haptic feedback guiding the user to maintain the correct cutting speed.

- **Feasibility:** Tactile haptic feedback not feasible.

Concept 10: **Non-essential, Immediate terminal feedback, Abstract mapping, Average, Knowledge of results, Quantitative, Multi-error response, Descriptive, What went right, Internal, Correct**
- **Goal:** Awareness of how good the cut was.
- **Implementation:** User receives a score based on cutting straightness on an abstract mapping.
- **Feasibility:** May be feasible for deformation and pressure on knife.

Concept 11: **Facilitative, Delayed terminal feedback, Abstract visualizations, Summary, Knowledge of results, Quantitative, Multi-error response, Descriptive, External, Correct**
- **Goal:** Creating awareness comparing results with an expert.
- **Implementation:** Feedback through a visual chart comparing the user's performance over time to an expert's standard.
- **Feasibility:** Would be nice but is not feasible.

Concept 12: **Facilitative, Concurrent feedback, Abstract mapping, Bandwidth, Knowledge of performance, Quantitative, Single-error response, Descriptive, What went wrong, Internal, Correct**
- **Goal:** Giving feedback about the cutting angles during cutting.
- **Implementation:** Bandwidth feedback indicating the range of acceptable cutting angles with abstract mapping.
- **Feasibility:** May be feasible.

Concept 13: **Essential, Concurrent feedback, Realistic visualizations, Fading, Knowledge of results, Qualitative, Single-error response, Descriptive, What went wrong, External, Correct**
- **Goal:** To let the user press against deformation of meat.
- **Implementation:** Instant feedback with realistic visuals showing deformation of the meat.
- **Feasibility:** Feasible.

Concept 14: **Facilitative, Concurrent feedback, Abstract mapping, Bandwidth, Knowledge of results, Quantitative, Single-error response, Descriptive, What went wrong, External, Correct**
- **Goal:** To let the user press against deformation of meat.
- **Implementation:** Change color of deformation of the meat to draw attention to deformation.
- **Feasibility:** May be feasible.

Concept 15: **Essential, Concurrent feedback, Kinesthetic, Fading, Knowledge of performance, Quantitative, Single-error response, Descriptive, What went wrong, External, Correct**
- **Goal:** To give haptic feedback of pressing against the meat.
- **Implementation:** Haptic device that represents meat that is able to deform.
- **Feasibility:** Feasible.

Concept 16: **Essential, Concurrent feedback, Kinesthetic, Fading, Knowledge of performance, Quantitative, Single-error response, Descriptive, External, Correct**
- **Goal:** To give the feeling of cutting meat.
- **Implementation:** Holding a knife and getting haptic feedback when cutting.
- **Feasibility:** Feasible.

Concept 17: **Facilitative, Delayed terminal feedback, Abstract visualizations, Summary, Knowledge of results, Quantitative, Multi-error response, Descriptive, What went wrong, External, Correct**
- **Goal:** Make the user aware of the progression of past cuts.
- **Implementation:** Show a graph of the performance of past 5 cuts.
- **Feasibility:** May be feasible for deformation and pressure on knife.

Concept 18: **Hinderance, Concurrent feedback, Kinesthetic, Fading, Knowledge of performance, Quantitative, Multi-error response, Descriptive, External, Correct**
- **Goal:** Make user cut straight.
- **Implementation:** Block any movement of the knife when not cutting good.
- **Feasibility:** Bad idea.

Concept 19: **Essential, Internal focus, Realistic visualization, Fading, Knowledge of performance, Qualitative, Single-error response, Prescriptive, Internal, Correct**

- **Goal:** Make user use non-dominant hand for holding meat.
- **Implementation:** Instruct user to grab the meat with a flat hand.
- **Feasibility:** May be feasible.

Concept 20: **Non-essential, Self-modelling/learner-modelling, Realistic visualization, Self-selection, Knowledge of performance, Qualitative, Multi-error response, Prescriptive, Correct**

- **Goal:** Awareness of others' faults.
- **Implementation:** Show previous recordings of yourself or other learners to evaluate.
- **Feasibility:** May be feasible but not necessary.

Then, all the concepts are also tested to see whether they add something to the research questions. The main focus of this research is the use of the non-dominant hand, so these will be important. The following concepts are important for the learning goal:

- **Concept 4**: Completely
- **Concept 11**: For deformation
- **Concept 12**: But for deformation
- **Concept 13**: Completely
- **Concept 14**: Might be useful
- **Concept 15**: Completely
- **Concept 16**: Completely
- **Concept 17**: Might be useful
- **Concept 19**: Might be useful

In the end, different concepts are chosen and combined, these concepts are all feasible to implement and are all important for the learning goal. These concepts are shown in Table 1.

Concept #	Change	Final concept
1	Without fading over time	Use realistic visualisations to display the ideal cut line in the VR environment.
2	-	Guide the knife action, similar to the expert, with haptic feedback along the correct path.
4	-	Use visual feedback to see the expert cutting the meat, so the student can imitate this.
11/17	Combined and only in textual representation where a grade is given for the performance of pressing against the deformation with the non-dominant hand	Feedback through text and grades comparing the user's performance over 3 times to an expert standard.
12	For deformation and with textual feedback	Bandwidth feedback indicating the range of acceptable deformation with textual feedback.
13	-	Instant feedback with realistic visuals showing deformation of the meat.
15	-	Haptic device that represents meat that is able to deform.
16	-	Holding a knife and receiving haptic feedback when cutting.

Table 1. All chosen feedback concepts

3.3 Interaction flow

The interaction flow is easiest explained using the flow diagram shown in Figure 3. This diagram illustrates the key components and sequence of actions involved in the meat cutting simulation process, starting from the top and progressing through each stage of interaction.

The interaction begins with the preparation phase, where the user puts on the VR headset and sees the knife and meat. From there, the flow proceeds to the positioning of the hands. The dominant hand is positioned to hold the knife while the non-dominant hand is placed flat on the meat to stabilize it. This positioning is essential for maintaining control and preventing meat from deforming during cutting. Next, the cutting stage begins. This involves applying a downward pressure to begin the cut. The cutting hand then executes a smooth, back-and-forth motion while the non-dominant hand plays a crucial role in holding the meat steady. By providing a firm pressure, this hand ensures that the meat does not deform and remains at a consistent thickness throughout the cutting process. The tactile feedback from this hand helps in adjusting the cutting motion to maintain evenness. Finally, the diagram illustrates the completion of the cutting process. This includes getting feedback whether the pressure given by the non-dominant hand was correct.

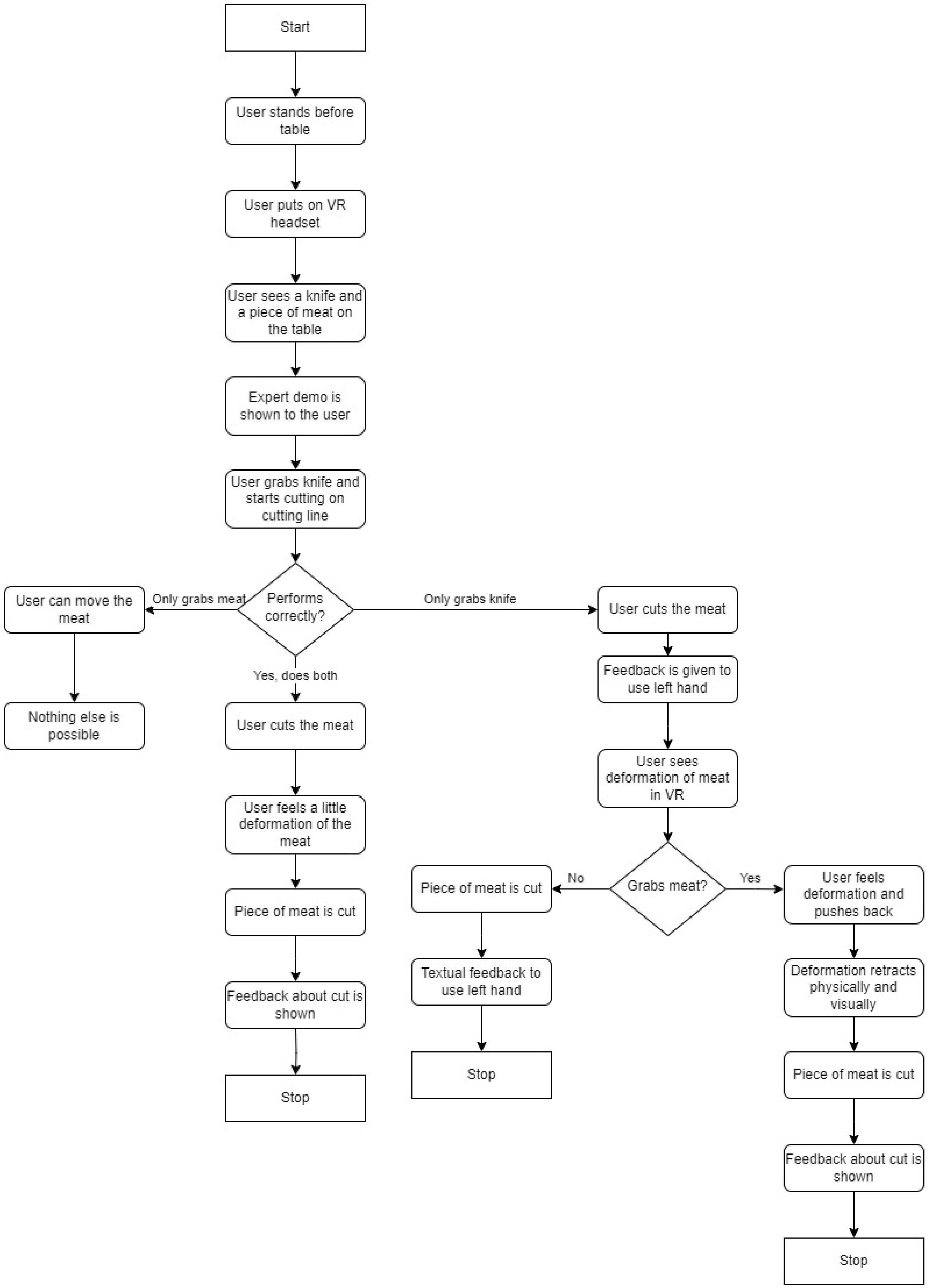

Fig. 3. Flow diagram of the meat cutting simulation process

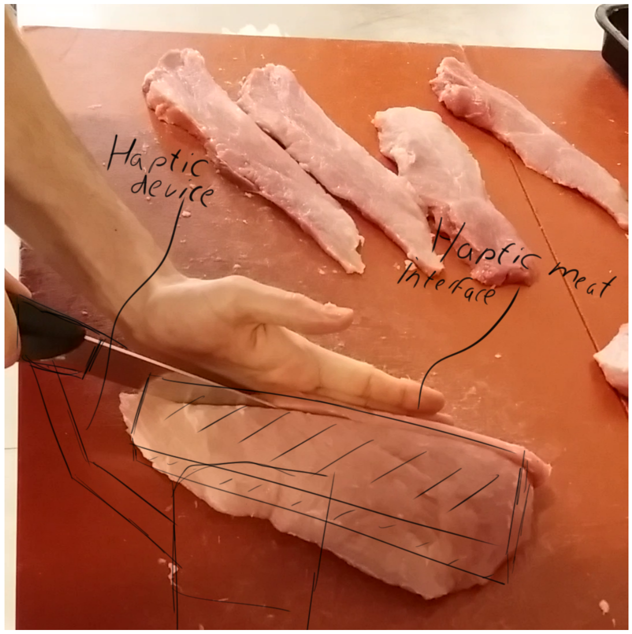

Fig. 4. Concept drawing overview

4 DESIGN

In this chapter, we will discuss the design process of the development of the complete learning experience. We will first give an overview on what is needed and then discuss the design and programming of the knife and meat, then also detailing how the physical and virtual models are synchronised. We then move on to the implementation of visual feedback mechanisms within the VR environment. Finally, we present the complete design.

The design should replicate the feeling of cutting real meat. An overview drawing of the intended design is shown in Figure 4. Here it is shown that the meat should be replaced with a haptic interface that acts and feels like meat and the knife should be replaced with a knifelike handle that is attached to a haptic device that is able to exert forces.

Some basic functionalities are needed for the creation of the learning environment. An overview of these functionalities with the current state is shown in Table 2. Starting with the knife, this device will be held with the dominant hand and should feel and look like an actual knife, both in VR and physically. The knife should track the position and rotation so this can be displayed in VR, and it should give haptic feedback when cutting through the meat. This can be done using a desktop haptic device like the Haply Inverse3.

Then, the meat will be held with the non-dominant hand. This meat should also feel and look like actual meat. But this physical meat model is more complex since it also includes deformation. This design should include the realism of holding a piece of meat and the deformation of meat while putting pressure on it. The visual model is already available.

The VR environment should be created similar to that of the butchery. This environment also includes the knife and meat and should integrate these devices so that it matches the real world devices. Also, visual feedback should be shown in VR.

4.1 Knife

The first crucial part of the butcher's experience is the cutting movement, including the knife and everything related to it. In this subsection, the steps taken to develop this knife cutting experience are explained. First, the physical design of the knife is explained and then the software behind the haptic feedback on the knife is explained.

4.1.1 Physical design. We first need to set the stage to get to the physical design. The haptic device used for this study is a Haply Inverse3 (see Figure 5). This device is capable of exerting forces in all 3 translation axes and can determine the position and rotation of a point in all 6 axes. The device consists of the Inverse3 and a handle. The Inverse3 is the system that is the interface for the determination of the position of the reference point, as well as the exertion of the forces. Attached to the Inverse3 is a pen-like

Overview functionalities	State
Physical model of knife	Model should be adjusted
Visual model of knife	Model available online
Haptics of knife	Programming should be done
Physical model of meat	Complete design should be made
Deformation of meat	Complete design should be made
Visual model of meat	Already available
Haptics of meat	Should be created
VR environment	Should be created
Visual feedback	Should be created
Integration of all devices	Should be created

Table 2. Overview of project functionalities and current state

Fig. 5. Haply Inverse3

handle, this handle is attached to the Inverse3 and can determine its own orientation. The Inverse3 and handle combined can define the position and rotation of the handle and exert translational forces on it.

The first challenge involves designing the physical knife itself. The Inverse3 handle should be integrated into this design to achieve all the functionalities of the haptic device. A 3D model of a real knife, similar to those used by butchers, was collected from the internet. This design was then 3D printed and after a few adjustments it was suitable to use as a physical knife in the 3D world while still being capable of using all the necessary functionalities of the handle. The handle and the 3D printed knife with the handle are shown in Figure 6.

Fig. 6. The Inverse3 handle (left) and 3D printed knife (right) next to eachother

The handle needs to be calibrated everytime at startup, otherwise the orientation of the knife does not match with the virtual orientation. To tackle this issue, a small hole is made for a paper clip to go into. In this way, it is still possible to press the calibration button on the handle without taking the knife apart, and it can also not be accidentally pressed while using the knife.

4.1.2 Haptics and programming. The physical design of the knife is needed to increase realism, but we still need force feedback to get the actual feeling of cutting. So, the second challenge was to implement this force feedback, which was a process that needed several steps to work. The next paragraphs will discuss the process of creating the software that calculates the force feedback on the knife.

Initial version. The first version of the software that is written for creating force feedback was made by *DiDutch*. This version is a demo to show how force feedback might work on a predefined line (see Figure 7). The working principle is that the cursor (which is linked to the handle) starts on the line. This is shown as the red ball in the simulation. This cursor can then move along the line without force feedback. However, when the cursor gets off the line, force feedback is generated. This feedback is calculated by determining the shortest distance between the cursor and the line, ensuring that the cursor (and consequently the knife) is always guided back toward the line. The corresponding force $\mathbf{F}$ applied to the cursor is described by Equation 1, where k is a stiffness constant, $\mathbf{p}$ represents the position of the cursor, and $\mathbf{r}(t_0)$ denotes the closest point on the line.

$$\mathbf{F}_{cut} = -k \cdot (\mathbf{p} - \mathbf{r}(t_0)) \tag{1}$$

Then, there is the blue ball that can be "pushed" towards the right by the cursor. When the cursor moves past the blue ball, force feedback is generated. This feedback is proportional to the distance by which the cursor exceeds the position of the blue ball. The generated force $\mathbf{F}_b$ can be described by Equation 2, where k_b is a proportional constant, $\mathbf{p}$ is the position of the cursor, and $\mathbf{b}$ represents the position of the blue ball.

$$\mathbf{F}_b = -k_b \cdot (\mathbf{p} - \mathbf{b}) \quad \text{for} \quad \mathbf{p} > \mathbf{b} \tag{2}$$

Additionally, as the cursor pushes the blue ball to the right, the blue ball moves in that direction. This simulates a cutting motion where the knife cuts deeper into the material. The movement of the blue ball, $\mathbf{b}'$, can be modeled by Equation 3, where $\mathbf{v}_b$ is the velocity of the blue ball and Δt is the time step.

$$\mathbf{b}' = \mathbf{b} + \mathbf{v}_b \cdot \Delta t \tag{3}$$

This software generates force feedback on the knife while cutting in meat. But the knife can only stay on the cutting line, so you are not able to move freely. Also, when cutting with a knife in a real-life situation the cutting action also results in that a lower force is needed to go through the meat.

Second version. A part of the previously explained cutting method is also used in the second version of the software. But only a straight vertical line is used which resembles the cutting down motion into the meat.

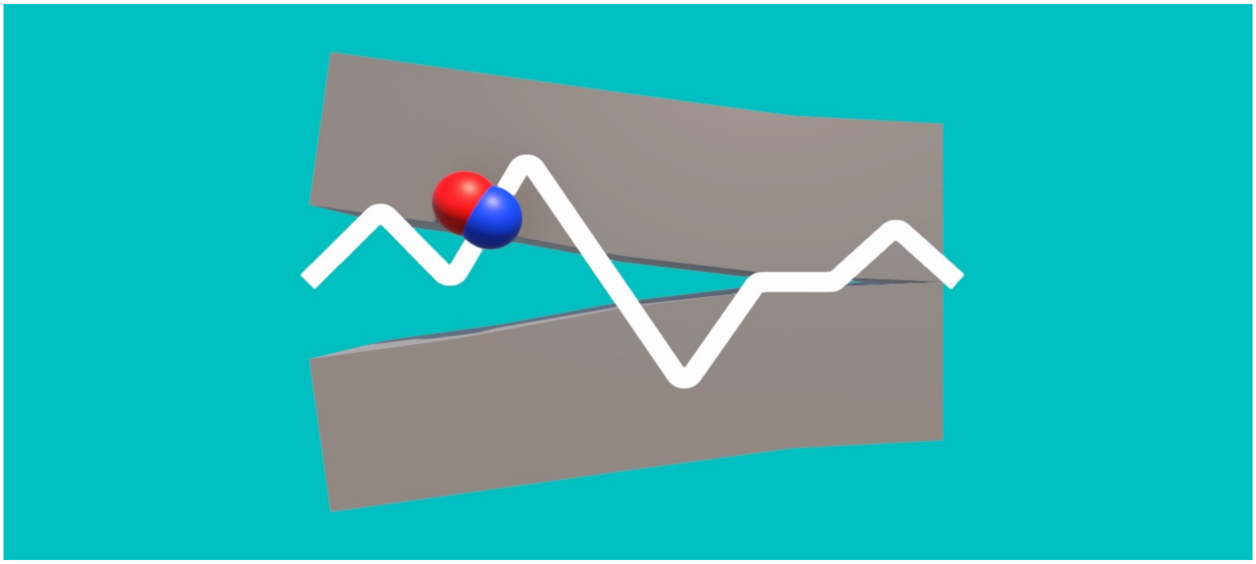

Fig. 7. First force feedback demo, the red ball resembles the position of the knife, the blue ball the amount that is cut into the meat

As described, using one line with this script is not enough, since it only defines one directional motion through the meat. To define the actual cutting motion, a second direction needs to be defined. This is done by adding an additional line and define the position of the knife on this line. This additional line is place orthogonal to the first line line and has a horizontal orientation. See Figure 8 for a visual representation of the lines.

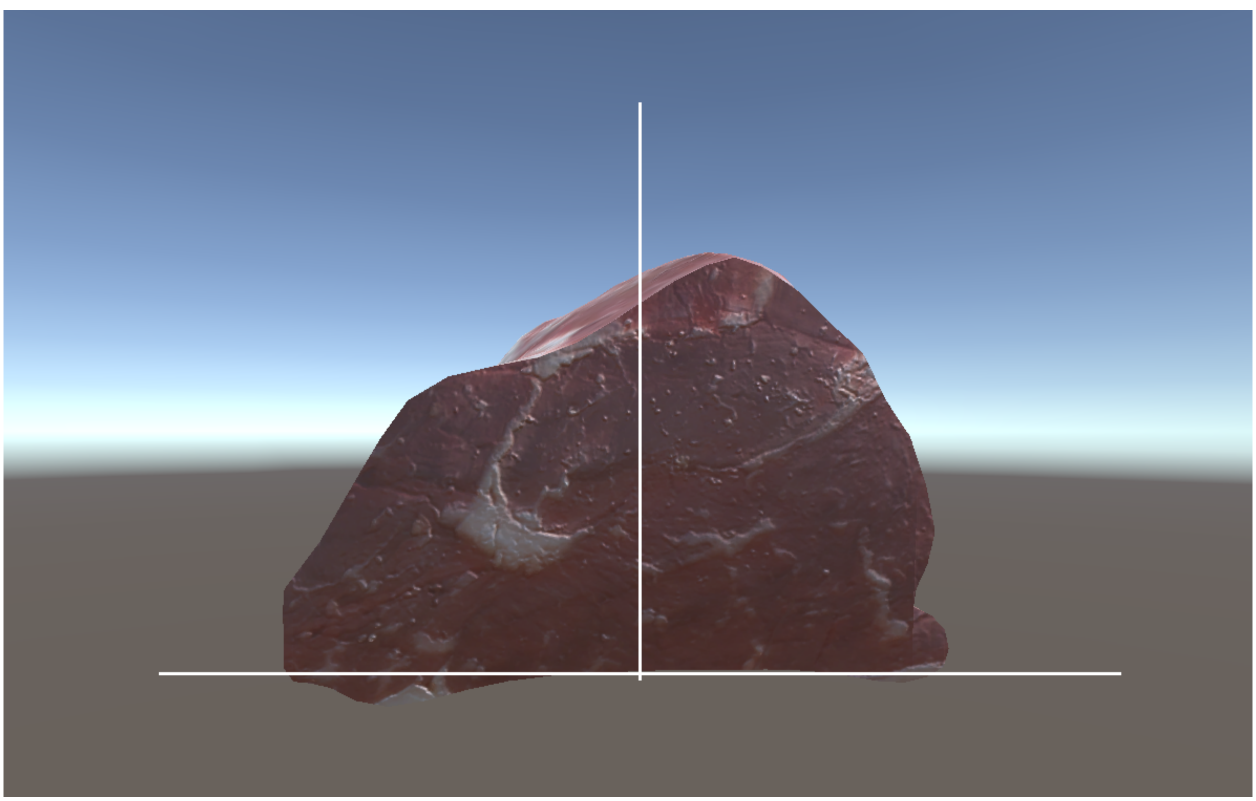

Fig. 8. Two lines to define force feedback on cutting motion

Each of these lines and scripts has its own implementation. The first line is placed vertically in the meat and defines the vertical position of the knife and the force required to cut into the meat. The second line is placed horizontally in the meat and determines the horizontal position of the knife. The horizontal speed of the knife, v_{hor}, reduces the force required to cut the meat with scaling factor α, $\mathbf{F}_{\text{cut}}$, as shown in Equation 4.

$$\mathbf{F}_{cut} = -\frac{k}{1 + \alpha v_{hor}} \cdot (\mathbf{p} - \mathbf{r}(t_0)) \tag{4}$$

In Equation 4, the horizontal speed, v_{hor}, is essential for making cutting easier, as it reduces the force required to cut down.

With these two lines, more realistic cutting force feedback is possible, and this cutting software is also used in further versions. The parameters that are used will eventually be tuned with a professional butcher.

Although it is now possible to cut the meat in a similar way to that of real-life cutting, this version still lacks the ability to move the knife freely and go off the cutting line.

Third version. The haptics of the learning experience still lack the ability to move the knife freely in space. To implement this functionality, a colliding script should be added to calculate the forces that normally occur when the knife hits an object. This was initially done with the *Unity* physics engine, with functions like *Physics.OverlapBoxNonAlloc* and *Physics.ComputePenetration* it is possible to determine the collision between two objects and to calculate the penetration. With the penetration and direction vector, it is possible to calculate the force that is needed to let the knife feel realistic. This way of calculating collisions is often used for games, but unfortunately, it is not sufficient for haptics in combination with VR. This is due to that haptics need a high refresh rate (>1kHz) to feel realistic and with using VR the refresh rate was 50Hz.

This is because of the main principles of Unity. The physics engine of Unity only works on the main thread; this essentially means that every computation is done after each other on one processor. This works fine when you only have a few computations and need very little of your CPU and GPU. But when VR is added, achieving these fast refresh rates is no longer possible because this requires much more processing power. So, this way of programming is not sufficient and the goal of the next version would be to achieve higher refresh rates.

Fourth version. Because we need to achieve a high refresh rate for the haptic device, we need to utilise a separate computing thread to do these calculations, a process called multithreading. Unfortunately, it is not possible to use any Unity API functions in a separate thread, because these only work on the main thread. So, it is necessary to do all the calculations of the colliders in a different way.

The thread used for this process is the same that performs calculations for the *Haply*. This is done to make sure that these calculations are done synchronously.

The first solution that was found, and which is relatively easy to implement, is by using the separate axis theorem (SAT). The SAT method will not be explained in detail because it is ultimately not used. The lesson that was taken by implementing SAT is that you can determine a collision very well with this method, it is fast to implement and it is a fast algorithm. Unfortunately, it is not suitable for this application because you are not able to determine the direction and penetration vector very accurately. This was not good enough for this application and felt unrealistic. The positive side of implementing SAT was that we found that using multithreading is the way to go for faster calculations for the haptic device and high refresh rates were achieved (>1kHz)

Fifth version. Another well-known algorithm in collision detection in game development was implemented, the Gilbert–Johnson–Keerthi (GJK) algorithm in combination with the Expanding Polytope Algorithm (EPA). GJK is first used to determine whether two 3D convex shapes collide, if this is the case, EPA is used to determine the direction and penetration vector of the collision. This direction and penetration vector can then be used to calculate the force feedback on the knife. An explanation of the GJK algorithm can be found in Appendix E and the explanation of EPA can be found in Appendix F. The combination of these algorithms is working; now it is possible to feel the meat with the knife as if it were a real piece of meat and a knife. The refresh rate is about 1kHz, so this is sufficient.

Final version. Now that everything is working separately, it is necessary to combine all the discussed functionalities in one haptic learning experience. The functionalities mainly consist of force feedback, these force feedback scripts need to be combined in a logical way. The flow chart of the generation of the force feedback is shown in Figure 9. There are essentially two options for generating force feedback, in the cutting state and not in the cutting state. When the knife is in the cutting state, it will generate a force feedback according to the cutting principle described in section 4.1.2. If it is not in the cutting state, it will generate feedback according to the collision detection with GJK and EPA. The colliding script will always generate force feedback on collision with different objects than the meat, this force will always be added to the output force. This is done so that objects like the cutting board can always be felt during the learning experience, also while cutting.

The switch from not cutting to cutting is done with a separate collider, if the knife enters this collider and it also collides with the meat, it will go into the cutting state. This separate collider is placed around the cutting line so it is possible to start with cutting there and not elsewhere on the meat. The switch from cutting to not cutting occurs when the knife does not collide with the meat.

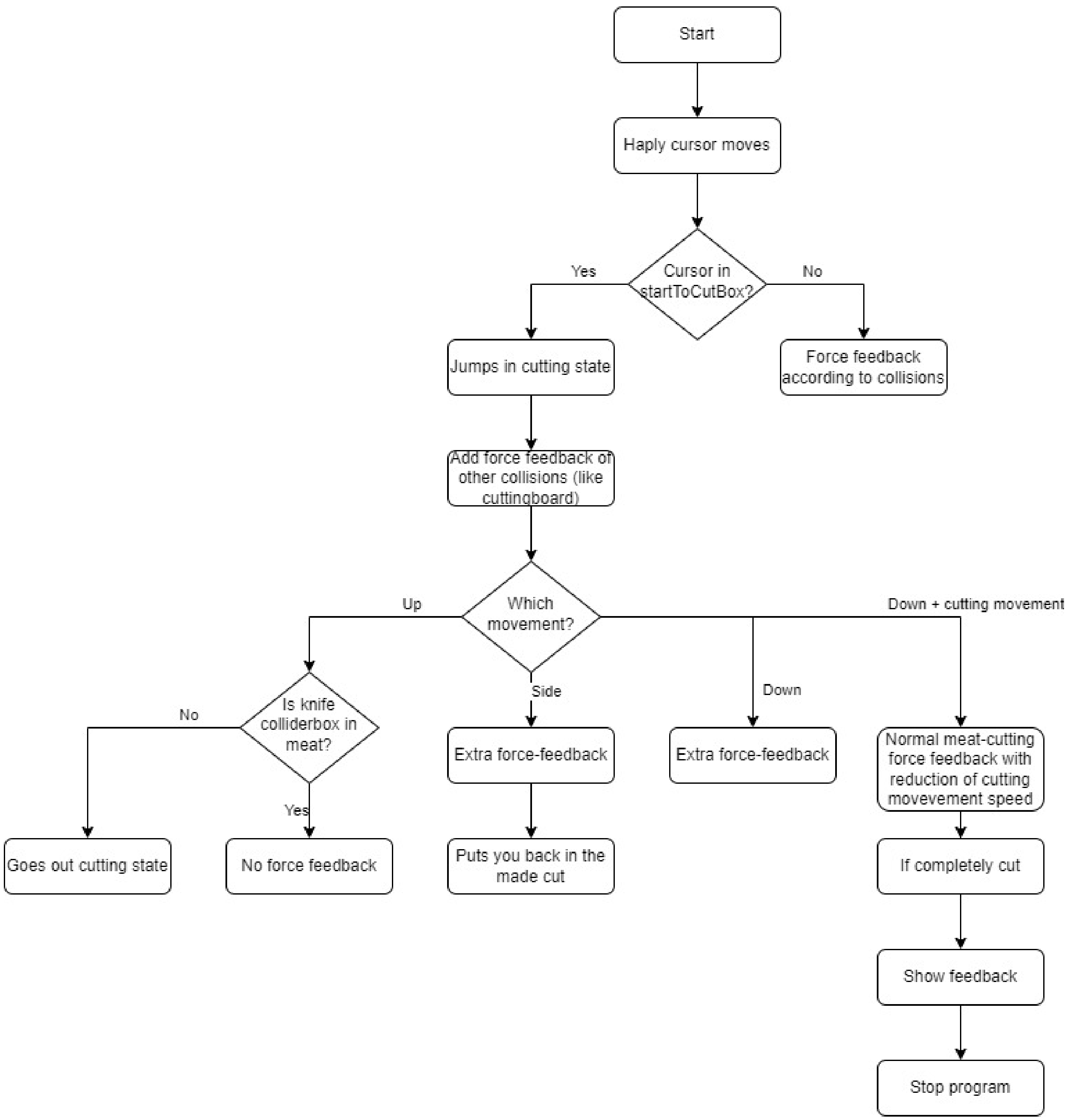

Fig. 9. The flowchart of the type of force feedback that should be generated for the knife.

4.2 Meat

The first essential part of the complete design was achieved with the knife in the previous subsection. But another crucial aspect of the design for this study is the physical and visual components of the meat. In this subsection, we will discuss all the steps that are taken to create a realistic physical and visual design as well as the link between the two.

4.2.1 Physical design. First, we will discuss the physical design of the meat, which was developed through an iterative design process. This began with the ideation phase, followed by multiple stages of refinement. Each step involved identifying and addressing various challenges, in the end leading to the final design.

Ideation. The first step in creating a physical haptic interface model for the meat was to create several ideas for the physical design, these were made by first deconstructing the design question into different challenges:

(1) The meat should be deformable like real meat
(2) The position or force which is applied to the meat should be sensed and communicated
(3) The meat should feel realistic for the non-dominant hand

Three high-level ideas were made for creating deformable meat as a physical haptic interface to understand what is possible. The first idea is to have active deformation, a deformation that is done by an actuator that is able to actively deform the meat according to what is sent to the actuator by Unity. The second idea is to use passive deformation, this is achievable with the use of a very soft silicone in a D-shaped model. The silicone should be soft enough to press against it to make it straight. The third idea is also based on passive deformation, but instead of having a thick layer of silicone, there is an air pocket behind the silicone that can give some extra deformation strength.

Real meat only deforms when being handled, when pushing the knife into the meat it will deform. To enhance the realism of the physical model, it was chosen to use active deformation, where an actuator is integrated to simulate the deformation of the meat. This approach allows to have an extra impulse for the non-dominant hand to stabilise the meat and push against the deformation. By adjusting the actuator's parameters, we can achieve various firmness levels, resembling the haptic experience of handling real meat.

An actuator is needed to create the active deformation of the physical meat. Several actuator types could potentially achieve this effect. One option is an air or liquid pump, which, when combined with an air pocket positioned behind a layer of silicone, could actively deform the meat by inflating or deflating the pocket. This setup would theoretically allow for dynamic changes in shape, closely simulating the way real meat responds to pressure.

However, this design is not without its challenges. The process would likely involve significant trial and error, especially in fine-tuning the system to achieve the desired deformation without compromising the integrity of the model. Problems such as air or liquid leakage, maintaining consistent pressure, and controlling the speed of deformation are likely. These issues could lead to unreliable performance, making the system difficult to calibrate and maintain.

Because of these potential drawbacks, this concept was deemed too complex and uncertain and was therefore abandoned.

The second option for an actuator is a rotational motor, with three primary types being considered: stepper motors, DC motors, and servo motors. Each of these actuators has the potential to effectively produce the desired deformation, but they come with their own advantages and disadvantages.

The stepper motor is a possible option due to its ability to offer precise control over movement, which is crucial for accurately replicating the deformation of meat. However, there is a significant drawback: stepper motors can sometimes skip steps, particularly under load or when rapid movements are required. This skipping not only reduces the accuracy of the motor's position but also introduces a noticeable, unnatural sensation in the meat model.

The DC motor is another possibility, particularly when paired with a positional encoder and a gearbox to provide the necessary control and torque. This combination allows for smooth and continuous motion, which is important for creating realistic deformations. However, integrating these components requires additional time and resources, making the system more complex and costly to implement. Given these considerations and because of the scope of this research, the DC motor setup was considered to take too long for this application.

The servo motor, on the other hand, emerges as the most suitable option. A servo motor includes an integrated gearbox and positional encoder, providing precise control over movement without the risk of skipping steps. Additionally, it is easy to control and implement, offering a reliable and cost-effective solution for the active deformation of the meat model. The ability of the servo motor to deliver smooth, accurate, and responsive motion makes it the ideal choice to achieve realistic simulation.

An overview is shown in the Pugh matrix Table 3 where all possibilities are tested on seven different criteria. This matrix shows that the servo motor has the overall best score and is chosen.

Criteria	**Air/Liquid Pump**	**Stepper Motor**	**DC Motor**	**Servo Motor**
Ease of Implementation	–	++	–	++
Precision of Deformation	+	+	++	++
Risk of Failure (e.g., Skipping Steps, Leakage)	–	-	+	+
Control Over Movement	+	++	++	++
Cost-Effectiveness	–	++	0	++
Complexity	–	++	–	+
Realistic Simulation	+	-	++	++

Table 3. Pugh Matrix for Actuator Selection

The position of the meat or the force that is applied should also be sensed for feedback to Unity. This can be done in many ways, but four are highlighted; using a capacitance sensor, flex/bend sensor, force sensor or a positional sensor. Depending on which concept is chosen, a certain sensor can also be used. Although all of them differ in functionality, it is possible to get similar results with these sensors.

We would like to highlight the capacitance sensor in combination with silicone since it is an interesting way to detect touch. This has been explored by Teyssier et al. [78]. They created a capacitance sensor with flexible, stretchable, conductive wire that can be put into a silicone mould. In this way, they can create an artificial skin that feels and can feel like skin. Unfortunately, for this design, it was not possible to use this sensor because of the availability of the sensor.

The choice of the sensor will be elaborated further in this chapter because it strongly depends on the choice of the concept design.

Silicone. The outer layer of the meat is made of silicone. The choice to use silicone was made for its texture and feel. This is a method that was proposed by Teyssier et al. [78] and is also supported by Angelika Mader and Gwenn Englebienne of the University of Twente. Silicone is used as an artificial skin in those applications, but can also be used as artificial meat.

To enhance the realism of the silicone mould, a texture was added to simulate the feel and appearance of real meat. Initially, six different textures were tested to determine which one would provide the most realistic sensation. These textures, illustrated in Figure 10, include four geometric patterns and two textures that more closely resemble real meat. After evaluation, the most realistic meat texture was selected. The texture chosen was that of real meat. The selected texture was initially 3D printed at a larger scale to facilitate a more thorough examination of its realism. Subsequently, the chosen texture was used to create a mould into which silicone was poured. The final silicone product was then evaluated by a professional butcher to determine its resemblance to real meat. The butcher's feedback indicated that the silicone texture closely approximated the feel and appearance of average real meat. This outcome confirms that the chosen texture successfully replicated the desired characteristics of real meat. The tutorial on creating a surface texture with SolidWorks is shown in Appendix M.

First iteration. Now that we have set the stage for what we need in a design, the first concept is made. This initial concept involves creating a system to simulate the physical characteristics of imitation meat using a servo motor and a rack-and-pinion transmission. The servo motor is responsible for controlling the position and applying force, while the rack-and-pinion mechanism converts the motor's rotational motion into linear motion (Figure 11).

The servo motor should take into account multiple things, such as torque, the possibility of soldering the potentiometer pin, and the use of metal gears. The best servomotor that can be chosen has exactly the amount of torque needed in combination with a transmission.

The concept is illustrated in Figure 12.

The primary focus of this iteration was to test whether the servo motor could yield under applied force, allowing the imitation meat to deform as expected. The servo motor that was used is the MG90S. To achieve this, the voltage and current supplied to the

Fig. 10. Meat texture tests, the first image consists of the 6 texture tests, the second image is trying the realistic meat texture on a bigger surface, the third image is the mould for silicone

servo motor were adjusted using a buck converter, specifically the XL4015 5A. By lowering the voltage to the minimum operational limit and fine-tuning the current, we aimed to reduce the force output of the servo motor.

However, controlling the force output introduced a challenge with the servo motor's startup current. Servomotors typically require a higher current at startup to overcome inertia. With the current limited to reduce force, the motor struggled to start consistently. To address this, a capacitor was added to the circuit to act as a temporary power reservoir, providing the necessary burst of energy during startup (Figure 13).

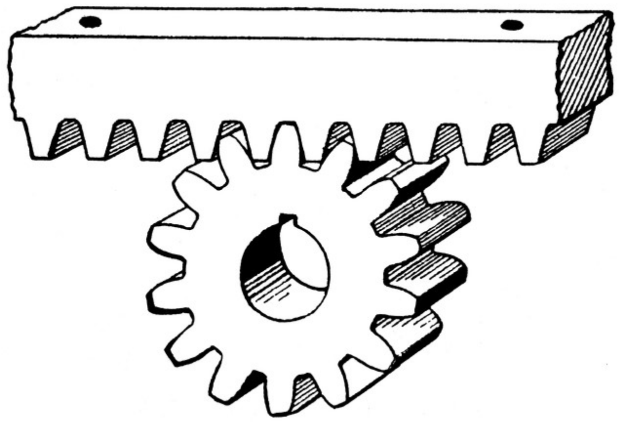

Fig. 11. Example of a rack and pinion transmission.

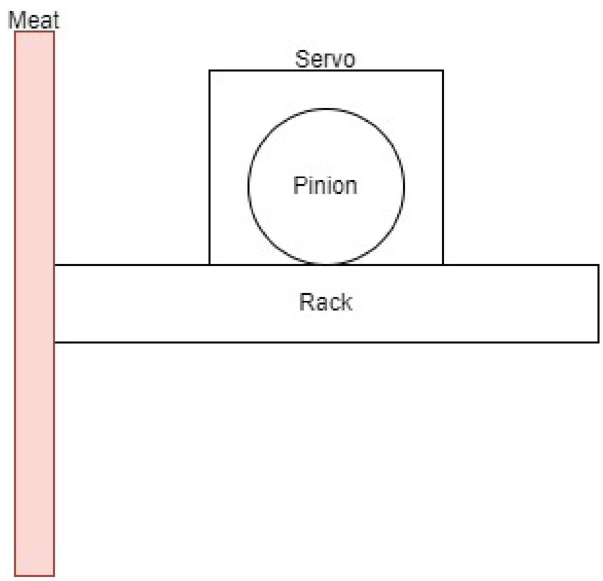

Fig. 12. Illustration of concept 1

Despite these adjustments, the servo motor's high holding torque remained problematic. High holding torque, while beneficial in many applications, prevented the motor from yielding as easily as needed when external force was applied. This issue highlighted the limitations of the servomotor in achieving the desired soft interaction. As a result, we explored alternative servomotors, such as the Graupner DES 708 BB MG, which has a lower holding torque and offers smoother operation. Unfortunately, this motor is overall too strong for this application.

This setup provides a balanced solution that is able to exert lower forces and can yield under external forces. Unfortunately, the perfect servo for this study was not found, and creating a custom servo, or using a DC motor, would take too much time. A different solution should be found in the next iteration.

This setup provides a balanced solution that is able to exert lower forces and can yield under external forces. Unfortunately, the perfect servo for this study was not found, and creating a custom servo, or using a DC motor, would take too much time. A different solution should be found in the next iteration.

Second iteration. The solution to the problem encountered in Concept 1 was effectively solved by using a spring in the system to simulate the stiffness and deformation characteristics of meat. In this improved design, the spring is placed between the motor and the flexible imitation meat. This configuration allows the motor to not only move the meat but also adjust its stiffness. By selecting

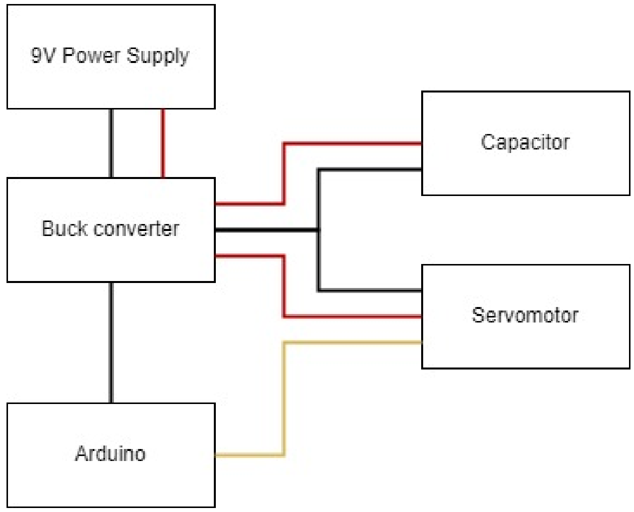

Fig. 13. Diagram of the connection of the servomotor.

a spring with appropriate stiffness, which should be relatively low to mimic the softness of meat, the system achieves a more realistic simulation. An overview illustration is shown in Figure 14 where the spring is placed between the rack and the meat.

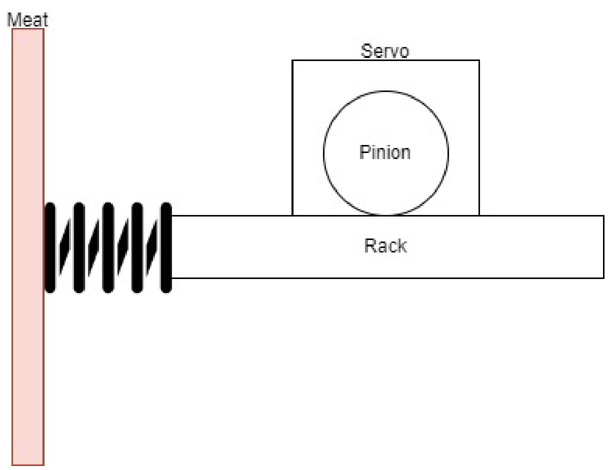

Fig. 14. Overview illustration of concept 2

As shown in Figure 15, the motor is connected to a rack and pinion mechanism, which in turn is connected to the spring. The spring acts as a flexible element, adjusting the overall stiffness of the meat model as the motor moves. This setup ensures that the deformation of the meat can be adjusted to simulate various levels of stiffness and response accurately.

The detailed implementation of this concept is illustrated in Figure 16. In picture 2, the pushing element connected to the spring is shown. This pushing element is responsible for applying force to the flexible, 3D-printed component that provides both the necessary stiffness and the ability to deform realistically, as shown in picture 3. The final assembly, including the silicone layer that covers the meat model, is displayed in picture 4. This silicone layer enhances the realism by providing realistic surface texture and flexibility.

This is a working concept that fixed the problems of concept 1, the motor is now only used to move the spring element and the spring element acts as the stiffness of the meat. However, this concept also raises additional problems such as that this is not suitable to use in a cutting board and next to the *Haply Inverse3* since the concept is too big.

Third iteration. Concept 3 is done to redesign Concept 2 so that it can be used on a cutting board and so that the *Haply Inverse3* can be placed closely. Concept 2 shows that the motor and the rack and pinion system takes a lot of room behind the meat which

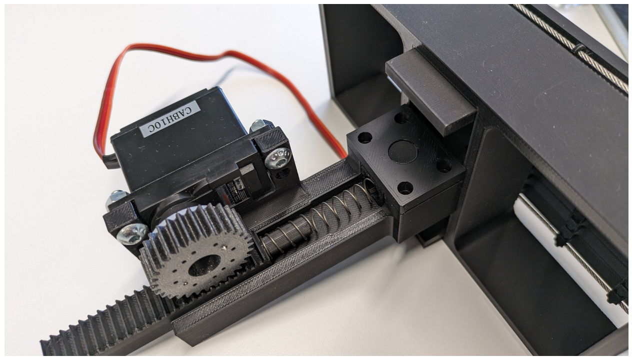

Fig. 15. Concept 2: Add spring between motor and meat

means that the *Haply Inverse3* and the physical meat may collide. The whole system should fit in a thickness of 25 mm (cutting board thickness), and should also go to the side of the meat. The goal of this iteration is to solve this problem.

This concept changes the transmission system; the rotational force of the motor is now converted to a translational force by the use of steel wire that is connected to a tension spring (motor and spring in pictures 1 and 2 Figure 17). When the motor rotates, it will pull on the spring, which then causes the meat to deform. This tension spring is connected to the pusher element that pushes on the meat deformation. This pusher is connected with a linear rail and carriage to the physical world to ensure smooth movement of the pusher (pictures 3 and 4 Figure 17). The complete concept is shown in picture 5 of Figure 17.

This proof of concept works and is verified by a professional butcher. The butcher indicated that it feels very similar to the actual deformation of meat, the only thing that is different is that the pusher of the meat should be positioned more at the bottom of the meat, where the meat normally touches the cutting board.

Final design. The final design is the updated version of concept 3, with multiple improvements. The improvements include the addition of a linear potentiometer to sense the position of the deformed meat, also the cutting board is added where the *Haply Inverse3* and a controller holder are mounted, and the third concept is changed so it can fit on the cutting board where the pusher element is located more at the bottom.

The linear potentiometer was selected as a sensor because it can be directly connected to the pusher element, accurately representing the position of the meat's deformation, and being easily accessible. In addition, the linear potentiometer is chosen because it is able to accurately determine the position of the meat without significant deviations.

The first picture of Figure 18 is the overview picture of the final concept. The *Haply Inverse3* is now also visible and mounted on the right side. There is enough space between the meat and *Haply Inverse3* to cut through the meat with the knife without colliding with the other objects on the cutting board. The implementation of concept 3 is shown in the second picture of Figure 18 where you can see the backside of the cutting board. The motor is located on the left side of the picture, with the steel wire running towards the tension spring holder. This holder also contains the linear potentiometer, which is also connected to the pusher (pictures 3 and 4 of Figure 18). The fifth picture of Figure 18 shows the overview of the backside of the meat, the motor is now located at the side of the meat where the hand does not go past to get to the meat. Also, the controller holder is also placed on that side, it is placed right to the motor on the fourth picture and left to the meat on the overview picture.

For now, the cutting board is an aluminium plate with wood underneath, all in the same sizing as an official cutting board.

The final concept is tested with a professional butcher and with seven butcher students. This will be further described in the next chapters.

4.2.2 Virtual design. Now that we have created the complete physical design of the meat, the focus is on the virtual design of the meat. The model that is used is a rib-eye. The company DiDutch scanned a real rib-eye to create a realistic virtual model of it. This highly realistic 3D model is shown in Figure 19.

To let the meat be more interactive and more realistic, deformation of the meat has to be made visible in *Unity*. This is done using shape keys in *Blender* to define certain deformation parameters. The meat is deformable in three ways, the first way is when pushed from above, the meat will deform on the cutting line as if the knife really pushes on the meat (picture 1 of Figure 20). The

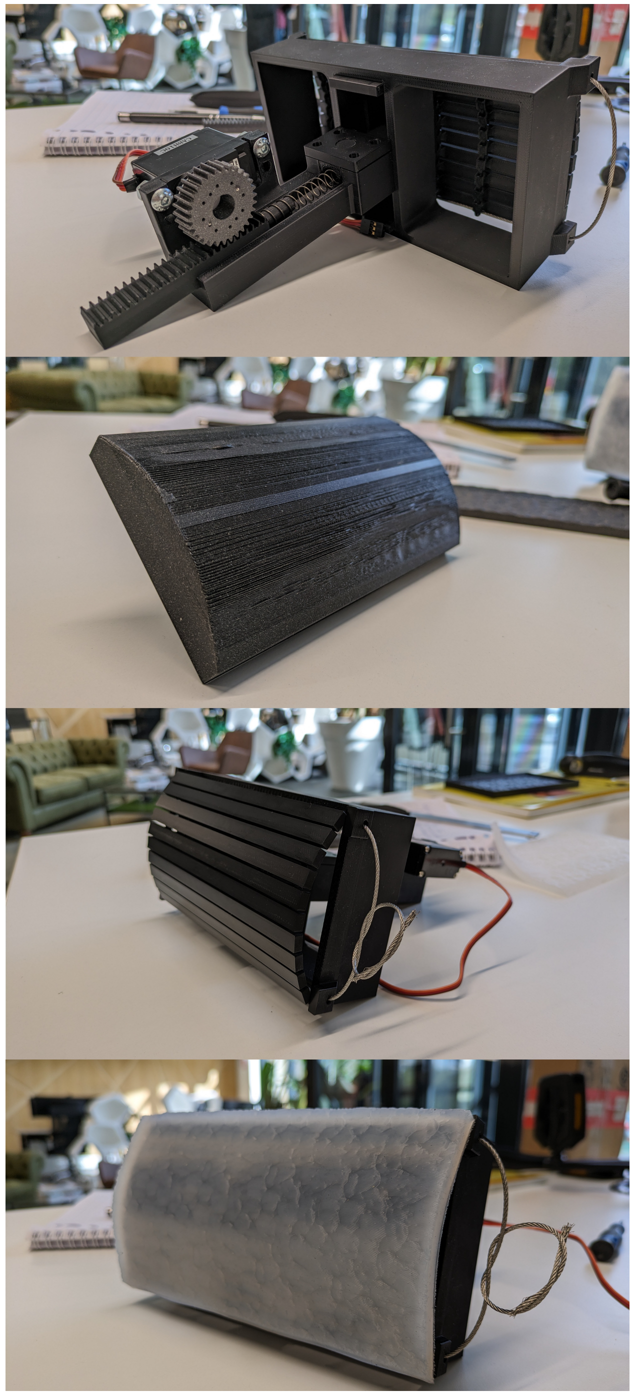

Fig. 16. Complete visualisation of concept 2. Picture 1: overview from motor side, picture 2: the pushing element connected to the spring, picture 3: the flexible 3D print on the frontside, picture 4: complete concept with silicone layer

second way is that when pushing on the side, the meat will deform from side to side (picture 2 of Figure 20). The third way of deformation is when the knife pushes down on the meat, the front surface area of the meat will bulge (picture 3 of Figure 20).

4.2.3 Link physical with Unity. The virtual world should be able to communicate with the physical world and vice versa. Because both the servo and the potentiometer exchange data to work. The servo and linear potentiometer are controlled by an *Arduino Uno*. A plugin called *Uduino* is used for the connection between the *Arduino* and *Unity*. This makes it easy to communicate between the two and makes it possible to control this connection. The *Arduino* collects data from the linear potentiometer, which represents

Fig. 17. Complete visualisation of concept 3. Picture 1 and 2 show the working principle of this concept, picture 3 and 4 the overview with the pusher and picture 5 the final overview of concept 3

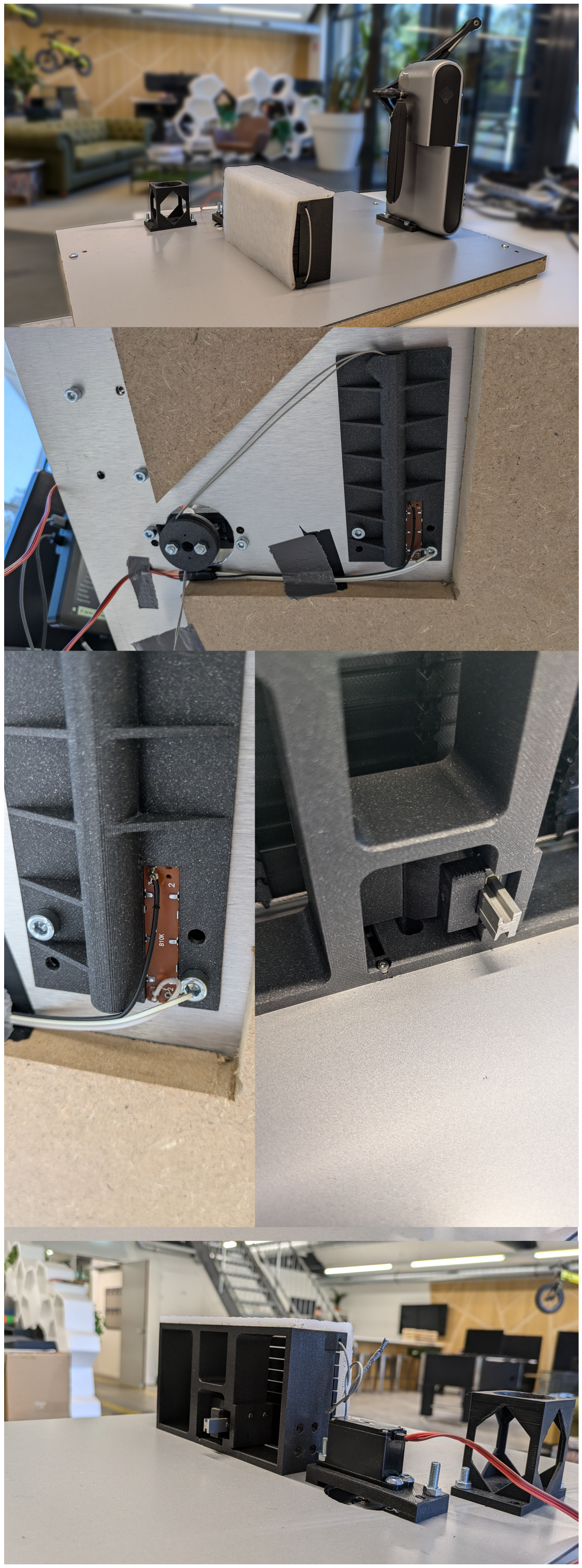

Fig. 18. Complete visualisation of the final concept. Picture 1 is an overview picture of the complete final concept. Picture 2 is an overview of the backside of the cutting board. Picture 3 and 4 show the location of the linear sensor. Picture 5 shows the overview of the meat, motor, and controller mount.

Fig. 19. The virtual meat model that is used in VR

the amount of deformation of the meat, and sends this to *Unity*. *Unity* collects this information and also sends the desired position of the servo to the *Arduino* which then goes to that position.

Programming of deformation. The deformation of the meat is first programmed in *Unity*. The force that is exerted on the knife directly translates to the amount of deformation in that direction, with a certain mapping to stay within the deformation range. So, for example, if the force on the knife is vertical, the meat will bulge on the flat surface and the meat will deform on the cutting line. This deformation is then shown in *Unity* and the amount of deformation of the flat surface is sent to the *Arduino*. Then, the *Arduino* will turn the servo according to the signal received to change the amount of deformation of the physical meat. At the same time, the potentiometer is read, and this data is sent back to *Unity*. This data is then used in *Unity* to show the actual deformation of the flat surface.

4.3 Matching physical and virtual

To ensure alignment between the physical and virtual environments, the positions and orientations of the knife and meat in VR must accurately align with their physical counterparts. Since both the knife and meat are fixed on the cutting board, knowing the board's position allows us to determine their exact locations. To achieve this, the left VR controller is attached to the cutting board, as it can track its position and rotation relative to the VR headset.

To do this in Unity, a startup scene was created, displaying only the VR controllers. The X button of the left controller needs to be pressed to continue to the next scene. This ensures the correct position of the controller in *Unity*. When scenes are changed, the virtual position of the VR headset is adjusted according to its relative position to the cutting board. In this way, the cutting board and so also the meat and knife are always located at the exact position of their physical counterparts. The downside of this method is that the entire cutting board and everything on it must remain in a static place.

To make the complete implementation of the design more realistic, an illusion has been applied. This is needed because the *Haply Inverse3* needs space to move, and the physical meat also needs space; this combination results in an unrealistic placement of the knife towards the physical meat. The illusion used is called redirected touching [38] and is used in this design to map the

Fig. 20. The three ways of deforming the virtual meat. Picture 1 shows deformation from top, picture 2 shows the side-to-side deformation, picture 3 shows deformation on the front surface.

knife and the meat closer to each other in VR than in reality. In this way, it feels realistic what the participant sees, but in reality, it is not. It was chosen to relocate the knife to another position in *Unity* since the participant will continuously hold the knife but can let off the meat with the non-dominant hand, that is why it makes more sense to put the meat in the actual real position. This illusion is shown in Figure 21 where the right knife is the actual position in the physical world and the left knife is the place where it is shown in VR.

4.4 Visual feedback

In the previous chapter, the feedback ideation was done, see Table 1. The visual feedback concepts that are created are shown in Figure 22. Here, it can be seen which concepts have a certain implementation.

4.5 Final design

The final complete design is a result of all the different steps that are discussed previously in this chapter. The only thing that is not discussed is the creation of the VR environment. The VR environment is based on the butchery room of *SVO* in Zwolle,

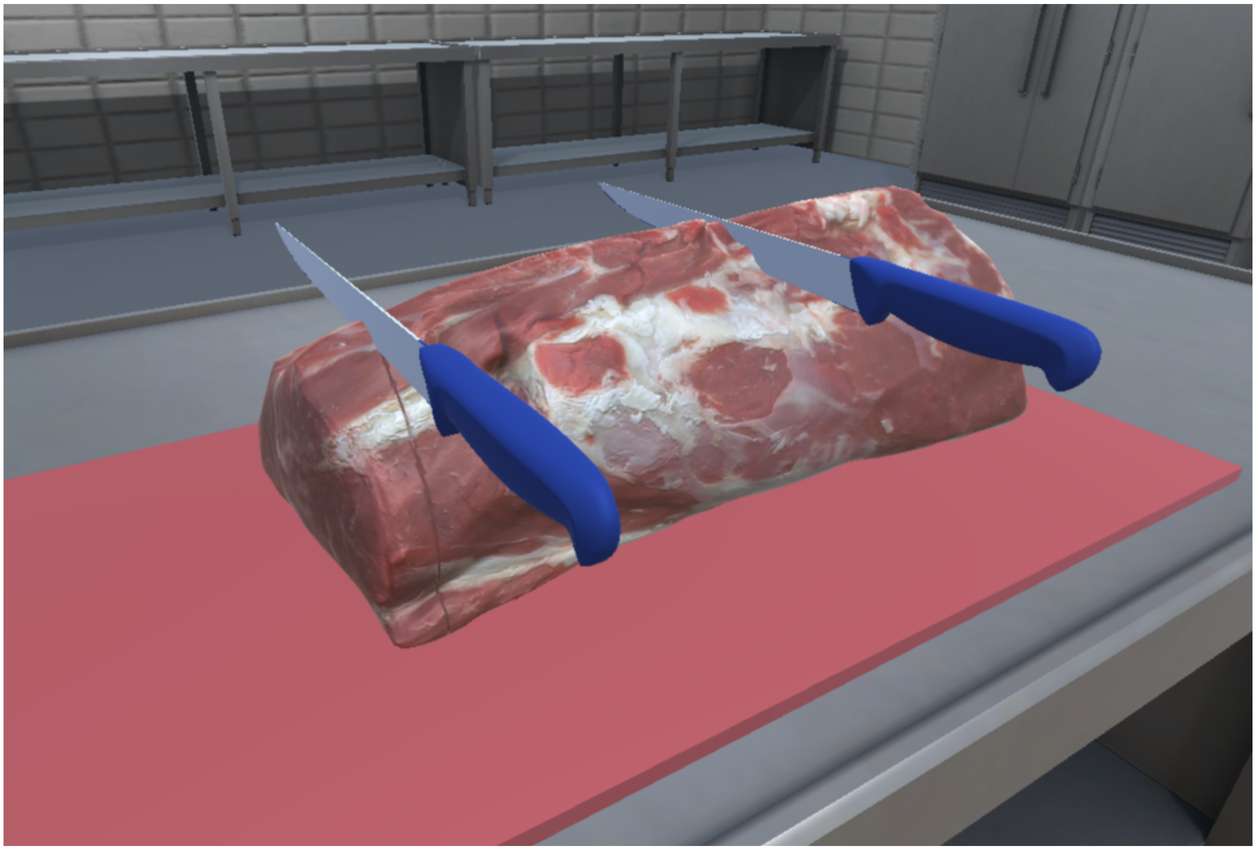

Fig. 21. Redirected touching illusion concept, right knife is physical position, left knife is shown in VR

the Netherlands, to make this environment as realistic as possible. In addition, red cutting boards are always used for red meat. Everything works together and is fully functional as intended. The video of the learning environment can be found in Final Design and the video of the butcher and students cutting can be found in Recording Playback. Also, a simplified schematic overview of the connection between the seperate components is shown in Figure 23.

All used software and programming information can be found in Appendix G.

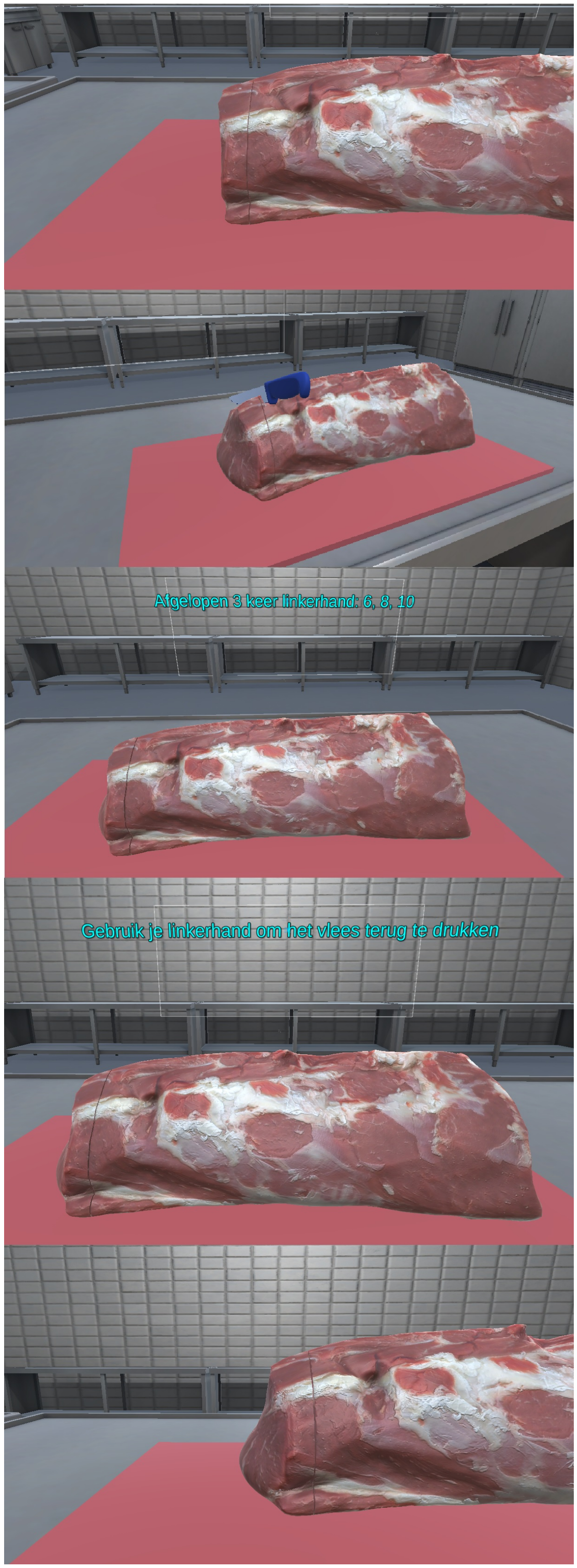

Fig. 22. Feedback concepts: Picture 1 corresponds to concept 1, picture 2 to concept 4, picture 3 to concepts 11/17, picture 4 to concept 12, picture 5 to concept 13

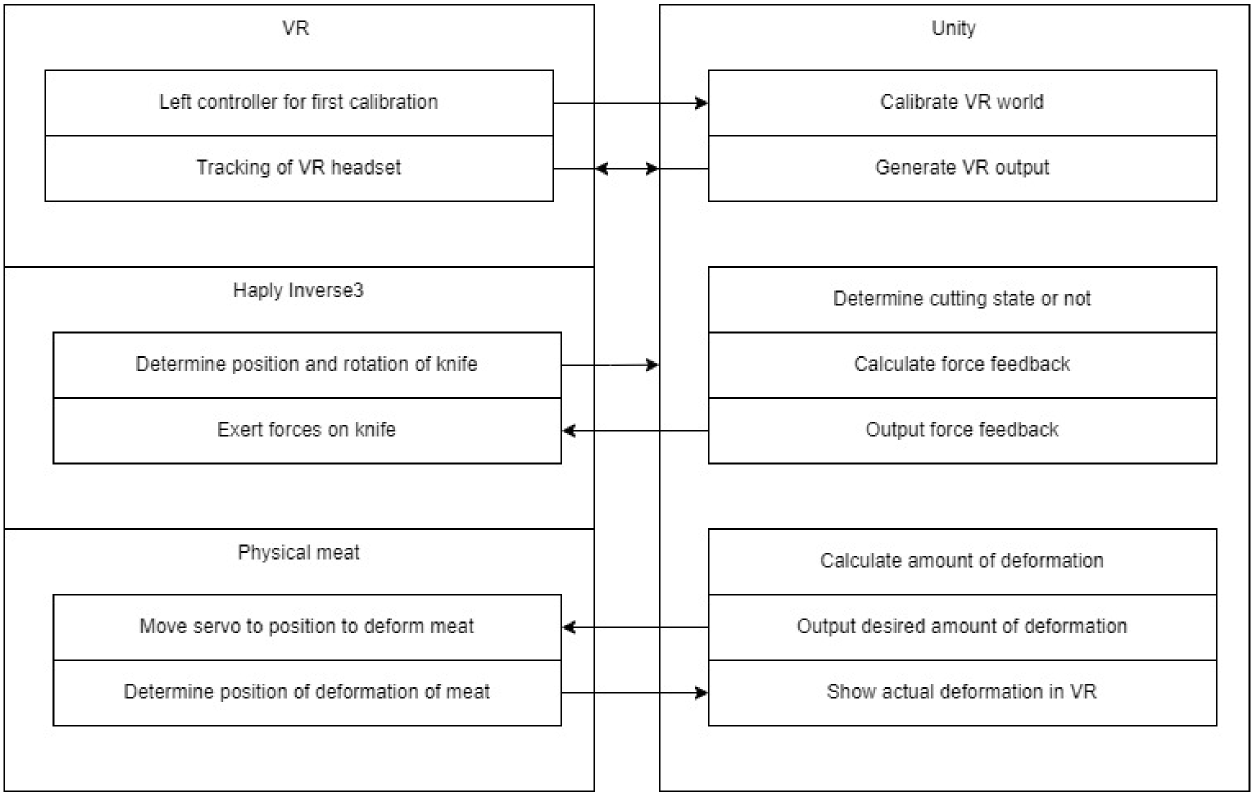

Fig. 23. Simplified schematic overview of the separate parts of the final design

5 EVALUATION

Participants: The study involved seven participants: seven students from the SVO butchery school in Houten. Among the students, six were right-handed and one was left-handed. The students were recruited in collaboration with the butchery school and their instructors. The students did have an intermediate level of meat cutting. They knew how to properly cut meat and can also distinguish different types of meat. These students were chosen because they already have experience cutting meat professionally and are still in the butchery school, so they are used to the standard learning environment. This would ultimately also be the target audience.

The study was carried out at the butchery school in a classroom environment in which students participated voluntarily. The role they got during these studies was that of a student. They engaged in a VR learning experience that simulated a butchery, allowing them to practice their cutting skills.

Theory: The goal of this study is to explore and answer the research questions that were already stated in the introduction:

RQ *How can haptic feedback enhance the VR learning experience of two-handed tasks in VR simulations for craft professions such as butchery?*
sRQ1 *How can a realistic 3D virtual and physical model be created of meat?*
  sRQ1a *How can the deforming of meat be implemented in both models?*
sRQ2 *How can the non-dominant hand be included in the learning environment?*
sRQ3 *What role does the non-dominant hand play in the interaction with the meat?*

The hypotheses of the research questions are as follows:
H1 *Haptic feedback on both hands will significantly enhance the VR learning experience of two-handed tasks by improving the user's ability to perceive force, resistance, and texture, leading to more accurate and intuitive manipulation of virtual objects.*
sH1 *A realistic 3D model of meat can be achieved by accurately replicating looks, feeling, texture, and deformation, which will enhance*

the authenticity of VR simulations.

sH1a *The deformation of meat can be implemented in both physical and VR models by developing a synchronized process that accurately represents the physical and visual properties and behaviours of meat.*
sH2 *The learning environment should include a physical design that requires active interaction with the non-dominant hand, as this will improve realism and enhance the overall learning experience.*
sH3 *Interaction with the meat using the non-dominant hand will provide more nuanced control and manipulation, improving the training outcomes in VR.*

The hypotheses in this study guide the research design and analysis. They predict the impact of specific features, such as haptic feedback and hand inclusion, on the VR learning experience. Data will be collected to evaluate these predictions, and the results will determine the effectiveness of the VR learning environment. The hypotheses will be discussed in the discussion section.

The study consists of two parts, one with the professional butcher and one with the seven students. The part with the professional butcher is done in multiple sessions. The first interview is conducted to get some sense of what important tasks are as a butcher. Because there are no reliable sources on the internet that discuss the tasks of a butcher this was essential to this research. The second and third interviews were performed to evaluate the design that was made. The third interview also consisted of getting the best and most realistic parameters for the haptic devices. These evaluations are essential for the study to improve the design, get good results from the final tests, and get qualitative results from a professional butcher. This part of the study will be discussed in the next paragraph.

Verification with butcher. Throughout the iterative design process, there were multiple occasions to discuss the topic with a professional butcher. This was done three times, the first time was to get a deeper understanding of what a butcher does and what elements are important. The second interview was to verify the design that was made. The third interview was conducted to record the motion of the butcher and also to tweak the parameters to make the haptics more realistic.

The interviews with the professional butcher were documented through detailed note-taking. The first interview was almost entirely transcribed to obtain comprehensive background information. This interview took about 15 minutes and can be found in Appendix D. The results of this interview were already discussed in section 2 and Appendix C.

For the second and third interviews, shorter notes were taken, focussing only on the questions relevant to the research. Both of these interviews were conducted in about one hour; this was longer because the design needed to be set up and because the design testing was also included. The butcher already had experience with VR which made it easier to conduct the tests in VR. While the butcher was performing the tasks, observations were also done.

The interviews with the butcher are analysed through the notes, these notes were then converted to useful information. This information is then used to evaluate and redesign the design. These steps were also discussed with the butcher to ensure the correct transfer of knowledge.

The notes of the second interview can be found in Appendix I. This interview was done to discuss all the progress that was made in the design. Also, design choices like switching from a pork chop to a ribeye were discussed, this cutting process is very similar. Another interesting point was the use of silicone to mimic the texture of meat for virtual reality training. While silicone isn't an exact match for ribeye, it offers a decent representation, though real meat feels cooler and wetter, which is something that could be simulated for a more authentic experience.

The knowledge gained was used to refine the design through an iterative process. The final design was presented to the butcher during the third and last interview. The butcher expressed positivity about the realism of both the physical and virtual meat, despite some minor deviations from the usual in terms of the knife's intuitive feel. During testing, the butcher also indicated that it felt unnatural to only use the knife for cutting, without using the non-dominant hand to hold the meat.

Our goal was to enhance the realism of both the meat and the knife, so we adjusted some parameters in Unity to achieve this together with the butcher. Specifically, we increased the amount of deformation of the physical meat and reduced the force required to cut through it, while also making other necessary adjustments.

Subsequently, the butcher's motion was recorded in Unity with both one hand and two hands. We later demonstrated the two handed recorded motion of the knife to the students to illustrate the proper cutting technique.

Participant testing. The second part of the study consists of extensively testing the design that was made during this study with the students. In the end, the results of this test are important for answering the research questions and important for the conclusion of this thesis. The study is done with a mixed setup in which both qualitative and quantitative questions are asked. The methodology, results, and discussion are based on this study.

Procedures: The tests with the students were performed in the corner of a classroom where no interference was possible from other people. Prior to the test, each student received an information letter outlining the research details and signed a consent form (see Appendix J). Subsequently, students were guided to the test setup where they were seated at a table. A detailed procedure was explained to them before they wore the VR headset; the complete protocol is available in Appendix K. The test sessions followed a randomised within-subjects design to mitigate bias, a necessary approach due to the limited number of participants. The participants did both variants of the test three times to collect more data to make it more stable. Each student test had a duration of about 10 minutes.

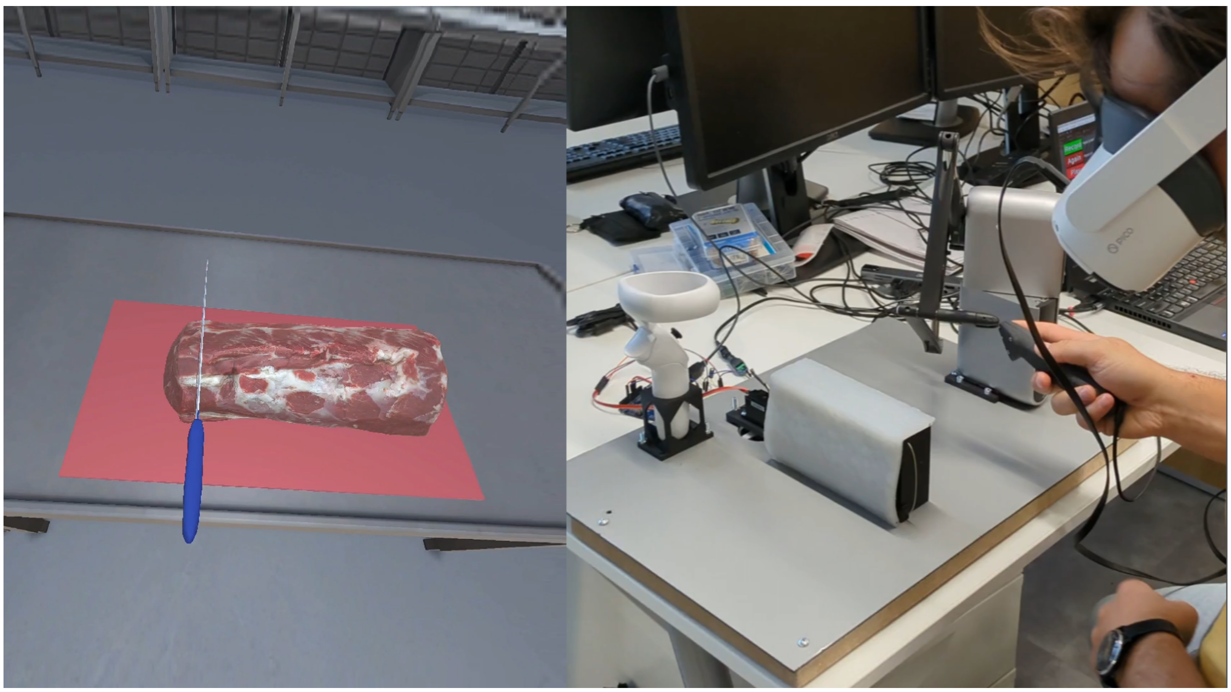

Fig. 24. Overview photo of the interaction with the physical and VR design

The VR setup that is used is with a Pico Neo 3 Pro in combination with the design which is described in the previous chapter. The overview photo of both the VR and physical design can be found in Figure 24. This is all connected through Unity. The custom Unity slider values that are used, and verified by the professional butcher, are:

- inputLimitSpeedMin = 2
- inputLimitSpeedMax = 100
- outputLimitSpeedMin = 5
- outputLimitSpeedMax = 30
- forceMultiplierX = 500
- forceMultiplierY = 3.5
- forceMultiplierZ = 100
- deformationStiffness = -80

Data from these tests were collected in multiple ways. The movement and rotation of the knife were recorded as well as the forces that were exerted on the knife. These recordings are all done in Unity, recorded in 30fps and saved in JSON format in different files. After the tests, a semi-structured interview with qualitative questions was conducted with the option to ask additional questions. Subsequently, a questionnaire was given with Likert scale quantitative questions, the interview questions and the questionnaire can be found in Appendix L. This setup ensures the complete and honest capture of the opinions of the students. Also, this setup ensures to have enough valuable data that can be evaluated. During the tests, observations were done and noted when it occurred more often for different students.

The butcher also performed the cuts three times with one hand and two hands to obtain a reference performance.

Analysis. The study with students utilized a 1×1 randomized within-subjects design. The two conditions were: (1) first using only the dominant hand, then using both hands, or (2) first using both hands, then using only the dominant hand.

The qualitative data from the interviews were thematically coded, focussing on recurring themes and notable observations. These codes were analysed to identify the most frequent opinions and to highlight remarkable notes.

Because for quantitative data there are few data points, seven per question, they are used in combination with the qualitative data to get a stronger confidence in the results.

We collected 5594 data points in total from the seven students. All the data points before the actual cut and after the actual cut were removed, this resulted in a total amount of data points of 3200.

This data is then analysed with data processing using Python. We present an analysis model for studies involving data collected from two-handed learning tasks. The flow diagram of this analysis method is shown in Figure 25. The data is recorded in JSON files, so first all data points are loaded from these files into a Python data frame. The data is then already split into students, butchers, and in both one-handed and two-handed actions. Two functions are written to remove all zero-forces from the top and bottom of the data frames; this is done to ensure that all data points are during cutting (so when there is force exerted on the knife).

Then, the first step in the analysis can be to calculate the mean and standard deviation to see if there are any atypical data points. Also, plot the box plots of both methods (one hand vs. two hands) next to each other of all data. With these box plots it is possible to gain more insight and already have indicators of statistical significance. It is also interesting to do this for the standard deviations of the data, for example, for the rotation of the knife. The rotation of the knife can be continuously wrong but can have almost no shaking or turning of rotation, this can still make it a good cut. Plotting the standard deviation of the rotation in a box plot can identify these kinds of problems.

Finally, it is very interesting to plot all the data in graphs, but before doing this, the data should be normalised. Normalising data for this data set means stretching all data to the same number of data points. Because every cut in the meat was of a different duration, all data is normalised and stretched towards the longest duration. This ensures that all data is presented in the same way. Now, the data can be plotted using various graphs, with each method represented by a different colour. For example, use distinct colours for one-handed student, two-handed student, one-handed butcher, and two-handed butcher. Outliers and anomalous data points can be removed after evaluating these graphs, resulting in more accurate and reliable data for drawing conclusions.

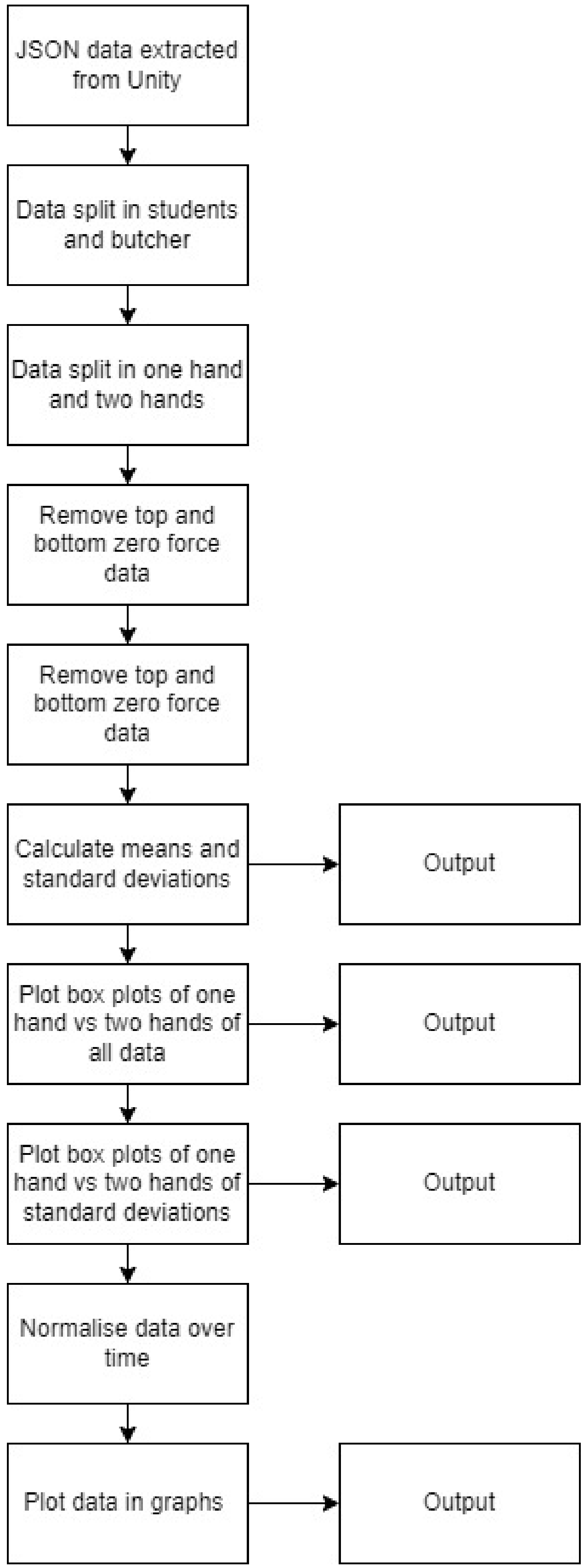

Fig. 25. Flow diagram of the data analysis method

6 RESULTS

This chapter presents the results of the study, organised into three distinct categories: Qualitative data, quantitative questionnaire data, and quantitative recorded motion data. Each section highlights the key findings relevant to addressing the research questions and exploring new insights.

6.1 Qualitative data

The qualitative data gathered from student tests are summarized in Table 4. These results highlight recurring themes and insights gathered from participants' responses. The themes were coded based on the frequency of how many participants mentioned them during the interviews.

Keyword/Subject	# Times Mentioned
Realistic	7
Positive about left hand	7
Awkward with only right	6
Realistic left hand	6
Not aware of posture	5
Cuts through more easily	5
Did not notice feedback	4
Feedback useful	3
Reference point missing	3
Posture changed	2

Table 4. The qualitative results coded by keyword or subject

As shown in Table 4, the themes mentioned most frequently include realism and the effectiveness of using the left hand, which suggest areas of strength in the test scenarios. In addition, less frequently mentioned but interesting points are shown in Table 5. These comments, while not as common, can provide valuable insights into specific aspects of the user experience.

Extra Feedback
Knife stutters a bit
Lacks structure in the meat while cutting
Normally, if you press harder into the meat, it goes further in
Tilting the knife should also affect the cut and you should be able to feel it
You don't want to cut into your hand
Being able to rotate and move the meat in VR
You want to actually cut the piece of meat off and see it afterwards
Cutting another piece of meat as well
Cold and slimy would make the meat more realistic
Knife clicks into the meat
Then you want to be able to continue cutting into the meat
A slightly longer knife

Table 5. The qualitative results that present occasional interesting points

Key elements that can be taken from the qualitative data are that all students found that the experience is realistic, where also six of them found that the meat feels realistic. They were also all positive about the use of the left hand and almost everyone found it awkward to use the right hand only to cut meat. Mainly, the students were not aware that their posture changed when cutting with one or two hands. Also, four did not see the textual feedback; this seems logical because these participants were good at giving pressure against deforming, and with bandwidth feedback, the concurrent textual feedback is not shown.

Another key element is that three students answered they were missing a reference point to cutting when the left hand was not included. From the answers, it becomes apparent that the knife is 'too sharp' and cuts through the meat too easily. The students also wanted to grab the meat, change its orientation, cut the next slice and watch the cut meat fall off the meat. All of these are aspects to which they are used to and would increase realism.

6.2 Quantitative questionnaire results

The results of the quantitative questionnaire, which all the students completed after their VR cutting experience, are presented in Table 6. The questionnaire aimed to assess various aspects of the VR cutting experience, including realism, feedback, and the educational value of the VR environment. The responses were recorded on a Likert scale from 1 (Strongly Disagree) to 5 (Strongly Agree). In addition, the mean and standard deviations per question are given.

Question | Participant	2	3	4	5	6	7	8	Mean	Std. Dev.
How realistic did you find the cutting experience in VR?	4	4	4	4	4	3	4	3.86	0.38
How did cutting with the knife feel?	4	3	4	3	4	3	4	3.57	0.53
How important did you find the visual feedback for your cutting experience?	3	3	3	3	3	4	4	3.29	0.49
How effective did you find the VR environment for learning cutting techniques?	4	4	3	4	4	2	3	3.43	0.79

Table 6. Quantitative results from questionnaire that used Likert scale

6.3 Quantitative motion data

3200 data points from students and 400 data points from the butcher were processed in Python. The results showing a difference in the outcome are shown in Figure 27.

The data that were analysed were the position and rotation of the knife, as well as the force that was exerted on the knife and the deformation of the meat. Box plots of the data were made, as well as the standard deviations of the rotations were plotted, to see whether there is a significant difference in using one or two hands. There was no significant difference found in this data, so this is not included in the results. Also, more graphs were made of all data, but these also did not result in significant differences, so these are also not included.

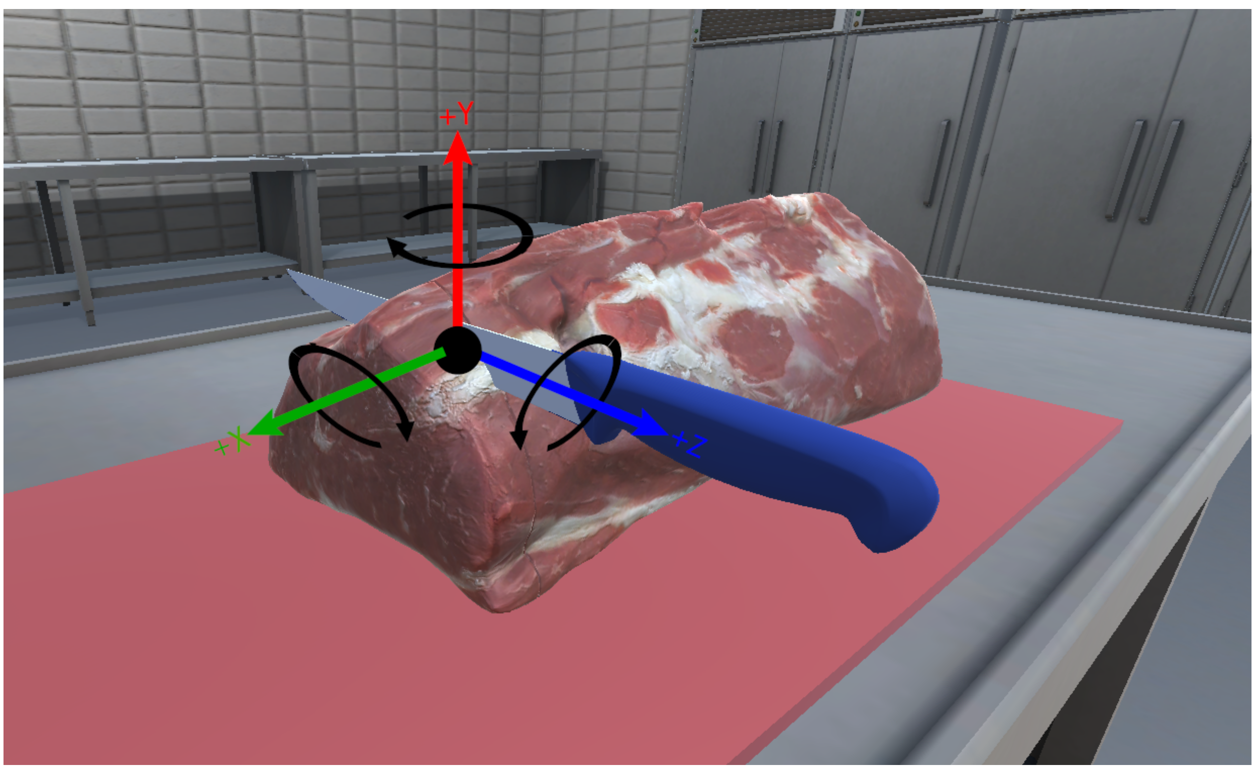

Fig. 26. Translation and rotation axes of knife

When looking at the graphs that contain differences (Figure 27, we can see that the butcher cuts differently than students in the four graphs that are presented. The Y position (up/down, see Figure 26) of the knife has a quicker decrease than the students, and the Z position (cutting movement, see Figure 26) has a curve, where the students cut a lot more straight. The X rotation of the knife of the butcher (up/down, see Figure 26) starts lower but ends higher. The Y rotation (into the meat, see Figure 26) of the knife of the butcher also starts lower. And finally, the maximum Y force (down, see Figure 26) that is exerted on the knife is achieved earlier when the butcher cuts, but is generally less often at the maximum than those of the students.

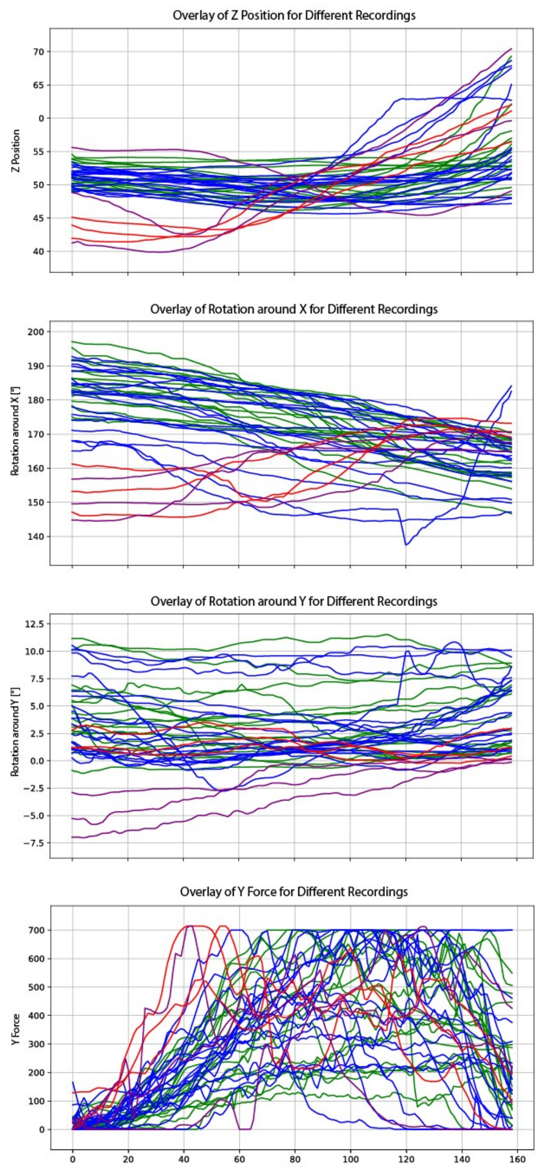

Fig. 27. Quantitative motion data. Green: Students one hand; Blue: Students two hands; Red: Butcher one hand; Purple: Butcher two hands

7 DISCUSSION

The results are presented in the previous chapter; in this chapter, we will discuss these results. The things that work and do not work will be discussed followed by the limitations of this study.

7.1 Qualitative Data

The qualitative data that was collected from the tests with students (Table 4) shows multiple important themes and insights about the VR learning experience. One of the important findings is that the experience was perceived as realistic, with all participants mentioning this aspect. All students were positive of using the non-dominant hand and six students specifically said that the implementation of the non-dominant hand was realistic. Six students also mentioned that cutting with only the dominant hand felt awkward. Three students even mentioned that when the non-dominant hand was not used, the reference point was missing. These are all indicators that show the importance of the use of the non-dominant hand while cutting. It should be mentioned that these students were already used to cutting with both hands, therefore, it makes it clear that using the non-dominant hand is more realistic. It is also interesting that three students indicated that a reference point is missing, since this was not a question that was asked. This emphasises the importance of using the non-dominant hand more.

Five students were not aware of the change of posture when cutting with one or two hands. Whether the students actually changed their posture without noticing this, is not recorded. That students would change their posture would make sense since your body changes posture when actively using different body parts. So, it is hard to say that the students did not really change their posture or that they just did not experience the change in posture.

One of the advantages of using VR to learn motor skills is that you can provide additional feedback to the environment. This was done with textual feedback in three ways for pressing against the meat; concurrent bandwidth feedback, terminal feedback, and terminal summary feedback. The students who put good pressure on the meat did not notice the feedback, probably because they were already doing this action in a good way. Students who did not apply enough pressure to the meat did notice the feedback and found it a good way to add additional feedback. This can still be an area of improvement where more intuitive or prominent feedback mechanisms might be helpful to ensure that important information is communicated effectively.

7.2 Quantitative Questionnaire

The quantitative questionnaire results provide further validation of the qualitative findings. The students rated the realism of the cutting experience relatively high, with a mean score of 3.86 out of 5, and the tactile feel of the knife also scored reasonably well at 3.57. These scores suggest that while the VR environment is quite effective, there is still room for improvement. Feedback importance and effectiveness for learning cutting techniques scored slightly lower, with mean scores of 3.29 and 3.43, respectively. Of course, there is always room for improvement but these scores are all indicators that this study points toward an effective learning experience.

The standard deviations for these scores indicate a moderate level of agreement among the participants, suggesting that while the overall experience was positive, individual experiences varied. This variability could be due to personal differences in prior experience with VR or cutting tasks, different skill levels, or different experiences, which should be considered in future designs and studies. When looking at participant 7, the scores he gave were overall lower than that of the other students. This may indicate that participant 7 experienced the learning environment differently from the other participants.

7.3 Quantitative Motion Data

The quantitative motion data analysis, which included 3200 student data points and 400 butcher data points, was designed to determine significant differences in cutting performance using one hand versus two hands. Despite extensive data analysis, including box plots and standard deviation plots for knife rotation and force exertion, no significant differences were found between the one-handed and two-handed methods. This result might indicate that both methods are equally effective in this specific controlled environment. With other methods these results may differ and would potentially get significant differences.

Although the motion data did not reveal any significant results, it still provided valuable qualitative insights into how realistic the interactions felt and highlighted the importance of more dynamic movements. Although the normalisation and plotting of the data were methodologically solid, incorporating more advanced analysis techniques or additional metrics might be necessary to capture the finer details of the cutting performance.

7.4 New insights

From all the data acquired from the tests with the students, we also gained new insights. For example, the experience of meat cutting with the knife and everything around that topic can still be improved. Five out of seven students said that the cutting of the knife was too smooth, cutting in real meat gives more feedback and also has more structure. Also, the students wanted to cut further on the meat and wanted to cut a slice of meat off the meat and inspect it. Additionally, the knife can stutter a little, the knife should be longer, and the knife clicks into the meat. Changing the rotation of the knife should also have influence on how the forces work on the knife and that the cut will be crooked. All of these points would give additional realism to the learning experience.

In addition, feedback was given on the physical imitation meat, where the students found that they would want to move the meat around and not let it only sit in one place on the cutting board.

Interestingly, a student reported experiencing a sense of reluctance to cut into their own hand during the learning experience. This reaction suggests a high level of immersion and indicates a significant degree of realism in the learning environment.

Another interesting point is the redirected touching illusion, described in section 4 and shown in Figure 21, where the knife's position is relocated in VR. Among the students, only one noticed the difference in the knife's location. The rest of the students remained unaware that the knife had been relocated and did not identify any inconsistency in its position.

Two students wanted to move and change the orientation of the meat, this highlights important considerations for the simulation's realism and interactivity. This preference could indicate that the simulation needs to be more realistic or that it is already realistic enough to prompt more interactive expectations, such as repositioning the meat. This level of interactivity is crucial for the learning task. Allowing students to adjust the meat's position can enhance their understanding and skill development, especially regarding correct posture and workpiece placement. Incorporating this feature could make training more effective and realistic, leading to better skill acquisition and practical application.

One student also indicated that he wanted to get force feedback when tilting the knife differently. Then the knife should get different force feedback where the knife automatically goes into the meat and also gets torque feedback making it harder to turn the knife. Unfortunately, this is not possible with the *Haply Inverse3*, this device is only able to exert forces on the translational axes and is not able to generate torque on the knife.

Looking at the quantitative motion data graphs in Figure 27, we can see some interesting differences between the cutting technique of a butcher and that of the students. In the first graph we see that, according to the Z position of the knife, the butcher cuts with more of a cutting motion than that of the students. This indicates that the butcher automatically cuts more like a real cut than the students. This also correlates with the five students who indicated that the knife cuts easily through the meat as if the knife is very sharp. If cutting is easy they might not use the cutting motion to go through the meat. These results may differ when the force on the knife is be higher when there is no cutting motion.

In the second graph it is made visible that the butcher has a different rotation around the X axis. Also here it is made visible that he makes more of a cutting motion where the knife is tilted with the cutting motion. The students show an opposite motion. This is probably due to that the students do not make a cutting motion.

In the third graph we see that there is a wide spread of rotation around the Y axis. The trend from this graph seems that the purple and blue lines are less stable, these are the recordings for using two hands while cutting. This is an interesting result because the hypothesis here is that cutting with two hands is more stable and so shows less variability, but this is not the case. An explanation can be that the participant has more focus on the main hand while cutting with only the main hand and that the implementation of the second distracts from the main task, cutting straight.

The last graph shows the force on the Y axis, so the cutting force. It shows that the maximum force on the knife was limited to 700. Interestingly we can see that the butcher hits this limited force scarcely and that the students hit the limited force more often. This was also one of the points that the butcher indicated in the interviews, that students often put too much force on the knife while cutting. These kinds of trends are very interesting and can be used for training certain skills in VR.

7.5 Limitations

There are a few limitations of this study, starting with the small test group. The test group only consisted of seven people, all students of a butchery school. With a small group it is only possible to get an indication of what the results mean. To tackle this problem, the testing should be done on a big group of a variety of people to get significant results.

This study was done for the specific use case as a butcher, but this approach can be applied to various other domains, the limitation of only one use case is that the results may not be applicable to other domains. These domains would also need testing to verify the results.

8 FUTURE WORK

Our study aims to explore asymmetric two-handed motor learning tasks using haptics and virtual reality. Our findings indicate that involving the non-dominant hand in VR learning improves realism and enhances the learning experience. The non-dominant hand's role in providing stabilizing force, like pushing against the deformation of materials such as meat, highlights its primary function in task realism.

To build on these promising results, future research should expand this approach to various learning domains that require similar asymmetric bimanual tasks. For example, in woodworking, the non-dominant hand can serve to stabilize materials while the dominant hand manipulates tools. In metalworking and sewing, similar learning tasks are involved, where the non-dominant hand plays a crucial role in stabilising the workpiece while the dominant hand is used for manipulating the workpiece.

Furthermore, specific design improvements in the VR environment could significantly enhance the realism and effectiveness of these tasks. Potential design tweaks could include more advanced haptic feedback mechanisms to improve the realism of the meat, improving the physical model of the meat so it can be moved, improve the VR experience so the meat slice falls of the meat and can be inspected, and the knife angle changes the force pattern. Also, it would be interesting to test whether it is important if the deformation of the meat is active or if it is also fine that this is passive.

In addition, in order to support the effectiveness of incorporating the non-dominant hand, it is important to carry out studies with larger and more diverse participant groups. Future research should explore the use of strong statistical methods to analyse the data. These models can account for individual variability and complex task interactions and can proof significance.

Beyond specific domains, the broader implications of this research could impact fields such as human-computer interaction, educational technology, and ergonomics. Understanding how asymmetric bimanual tasks are learnt and performed can lead to innovations in training programmes, tool design, and user interface development. Because we are now able to do a asymmetrical bimanual task in VR with haptics, we are also able to measure everything. Movement, rotations, and forces are easily recorded and analysed. This opens doors to new research in many fields.

Future research should also address potential challenges, such as the varying complexity of tasks across different domains and the technical limitations of current VR and haptic technologies. Suggested research questions include: How does the inclusion of the non-dominant hand affect learning efficiency in complex motor tasks? What impact does the level of haptic feedback have on task performance and learning outcomes? What impact has active or passive deformation of the haptic device that is designed for the non-dominant hand?

By exploring these questions and following the suggested paths, future research can enhance our understanding of motor learning in VR environments and expand the potential applications of this approach to a broader range of practical and educational scenarios.

9 CONCLUSION

This thesis aimed to explore the role of bimanual asymmetric haptic feedback in enhancing VR training environments, specifically within the context of butchery skills. The introduction highlighted a gap in existing research concerning the use of two-handed, asymmetrical haptic interactions in VR. This gap was particularly noticeable given the prevalence and complexity of bimanual tasks in various skilled professions. Through the research conducted, this work has successfully addressed the outlined goals and substantiated the claims made at the outset.

The primary contributions of this research are diverse. Firstly, it provides a novel empirical investigation into the application of asymmetrical bimanual haptic feedback in VR, demonstrating its role in enhancing the realism and effectiveness of virtual training environments. By focussing on the use case of a butchery, this study has extended the understanding of how haptic feedback can be used to improve skill acquisition in VR.

Looking back at the research questions set out in the Introduction we can conclude the following.

9.1 Answering research questions

sRQ1 *How can a realistic 3D virtual and physical model be created of meat?*

sH1 *A realistic 3D model of meat can be achieved by accurately replicating looks, feeling, texture, and deformation, which will enhance the authenticity of VR simulations.*

A realistic 3D model of the meat is created as a physical model and as a model in VR. Both models received positive feedback, indicating a strong imitation of reality. All seven students who evaluated the models found them to be realistic. The interview results further confirmed this, as the students expressed that the models closely resemble actual meat in terms of texture, appearance, and feel.

sRQ1a *How can the deforming of meat be implemented in both models?*

sH1a *The deformation of meat can be implemented in both physical and VR models by developing a synchronized process that accurately represents the physical and visual properties and behaviours of meat.*

The deformation of the meat was achieved in both the physical and VR models and synchronised through an iterative design process. This process was developed in collaboration with a butcher, and this design process can be found in section 4, resulting in functional and realistic models. Six out of seven students found the deformation of the meat and the connection between the physical and virtual models to be realistic. This indicates that the approach of this design is effective in creating a consistent and convincing representation of meat deformation in both models. The strong point of this design is that it is made in collaboration with a butcher and is relatively simple to make and implement.

sRQ2 *How can the non-dominant hand be included in the learning environment?*

sH2 *The learning environment should include a physical design that requires active interaction with the non-dominant hand, as this will improve realism and enhance the overall learning experience.*

The non-dominant is implemented in the learning environment by using a physical imitation meat model that actively deforms physically and visually, in response to forces applied by a knife. There are strong indications that this relatively simple interactive technique can enhance realism and improve the learning experience. Student feedback was overwhelmingly positive: all seven students appreciated the inclusion of the non-dominant hand with the active deformation, and six out of seven found the experience to be realistic. Additionally, students noted that cutting the meat without engaging the non-dominant hand felt unnatural. Three students also pointed out that they miss a point of reference when not using the non-dominant hand. These observations strongly indicate that incorporating the non-dominant hand not only enhances the learning experience but is also essential, as its absence modifies the natural flow of the task and reduces the realism of the simulation. This can also be a result of students already being used to cutting using two hands. But this still underscores the importance of realistic practice. By not using the non-dominant hand, the training becomes less effective, as it fails to replicate the actual conditions under which the skills will be applied. Thus, ensuring the involvement of both hands is important for developing skills in real-world scenarios.

sRQ3 *What role does the non-dominant hand play in the interaction with the meat?*

sH3 *Interaction with the meat using the non-dominant hand will provide more nuanced control and manipulation, improving the training outcomes in VR.*

By analysing the recorded motion data, we can not identify any significant differences in the quality of the outcome for the use of the dominant hand. The recorded motion data consist of the rotation, translation, and exerted force of the knife. The curves between one-handed and two-handed data are very similar, as well as the box plots that were made. So, there is no observable difference in the end result of the quality of the cut when one or two hands are used according to the collected data and used parameters. It could still be possible that with different parameters or different measurements, significance could be achieved.

Qualitative data showed that the non-dominant also offers a reference point for cutting. Unfortunately, this is not an outcome of the recorded motion data.

Of course, it is still essential to implement the non-dominant hand, since the complete learning task also consists of pressing against the deformation of the meat. If this is not done, the meat will deform and the cut would be of better quality.

RQ *How can haptic feedback enhance the VR learning experience of two-handed tasks in VR simulations for craft professions such as butchery?*

H1 *Haptic feedback on both hands will significantly enhance the VR learning experience of two-handed tasks by improving the user's ability to perceive force, resistance, and texture, leading to more accurate and intuitive manipulation of virtual objects.*

Haptic feedback is implemented in two ways, the knife offers haptic feedback when cutting the meat with the dominant hand, and the physical imitation meat offers haptic feedback of the meat and its deformation. The haptic feedback given by the knife was experienced as realistic enough, but can be improved. The haptic feedback of the meat is considered as a success since the realism of the learning experience is improved for all students. Although there is no significance achieved in the study, we have strong indicators that adding haptic feedback for asymmetric two-handed tasks in VR simulations will enhance the learning experience. This can be done by adding a relatively simple extra haptic device to the learning experience and syncing this in VR.

9.2 In conclusion

A key point is that we found strong indicators that the inclusion of the non-dominant hand in VR training enhances the realism of the training experience. Participants consistently reported that excluding the non-dominant hand resulted in an unrealistic and incomplete training simulation, thereby confirming the non-dominant hand's important role in achieving a comprehensive learning experience. This insight is important for designing future VR training systems that aim to replicate real-world tasks more accurately.

Looking forward, the implications of this work suggest a promising trajectory for the integration of bimanual asymmetrical haptic feedback in various domains beyond butchery. The methodology, design and findings of this study pave the way for broader applications in fields such as woodworking, where precise bimanual coordination is critical, and in other professions where mastering complex motor skills is essential. The potential for VR to transform training by offering a safe, controlled, and immersive learning environment is limitless, and this research contributes to this evolving landscape.

In conclusion, this thesis contributes to VR and haptic feedback research and opens up new avenues for applying these technologies in diverse fields. By improving the realism and effectiveness of VR training systems, this work points to a future where learning complex motor skills can be more accessible, effective and aligned with real-world demands. The progress outlined in this study offers potential for VR-based education and training, ultimately leading to a more skilled and prepared workforce in various industries.

10 ACKNOWLEDGEMENTS

First of all, I would like to sincerely thank my supervisor at *Dynteq*, Martijn Smit. His expertise and insights were incredibly helpful throughout my research. His practical guidance and support were crucial to the successful completion of this work.

I am grateful to my main supervisor at the University of Twente, Dennis Reidsma. His continuous support, insightful feedback, and encouragement have been a great source of inspiration and motivation for me.

I also want to express my sincere thanks to my second supervisor, Douwe Dresscher, for his valuable advice and assistance throughout this project. His guidance has been greatly appreciated.

My appreciation extends to Chris van der Leij from the *SVO* (butchery school). His contributions in deepening my understanding of butchery and providing critical feedback on the designs were invaluable.

A special thanks goes to *DiDutch* for their support and assistance, which contributed to the progress of this thesis.

I would like to extend my thanks to the participants who willingly took part in this study. Your contribution was essential and greatly appreciated.

I would also like to acknowledge Angelika Mader and Gwenn Englebienne from the University of Twente for their occasional but impactful help.

To my colleagues at *Dynteq*, thank you for your encouragement and help during this project. Your cooperation and mutual support made this journey both enjoyable and rewarding.

Lastly, I am deeply thankful to my family and friends for their continued support and encouragement throughout my studies. Your belief in me has been a driving force.

Thank you all for your invaluable contributions and support.

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A XR

The use of Virtual Reality (VR) dates back to a prototype from 1962, with the use of video, audio, and haptics to provide an immersive experience; the *Sensorama* [8]. Made by the "father of VR"; Morton Heilig, who even had to invent a 3D camera to let the *Sensorama* work [9]. Unfortunately, it never took off since it was not always comfortable to use this machine [9].
After that, one of the first working Head-Mounted Displays (HMD) was called the *Sword of Damocles* and was already invented in 1968. This device was able to track the head and eyes and change the images displayed accordingly [73]. However, due to the technical limitations of the time, it was not immersive.
In the years following, many products for VR were made but were always limited since the technical limitations were too big or too expensive [9]. Until the arrival of the *Oculus Rift*, the first affordable HMD with immersive functions in 2013 [22]. This was the start of the development of many VR headsets.

Since the release of this headset, a lot of developments have been made. These developments have caused a broader field than only VR, so X Reality (XR) was introduced. XR is the overarching term for all possible artificial realities where the variable 'X' functions as a placeholder, representing the diverse array of emerging realities [59].

A.1 XR Spectrum

XR is an umbrella term that encompasses various technologies that alter reality perception, such as Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR). These technologies differ in the degree of immersion, interaction, and information they provide to the user, creating different experiences of the physical and virtual worlds. One way to understand the relationship between these technologies is to use the MR-centered view proposed by Rauschnabel et al. [59], which places MR in the center of a continuum between AR and VR. AR is a technology that overlays virtual information on the physical environment, while VR is a technology that occludes the physical environment and replaces it with a virtual one. MR is a technology that blends virtual and physical elements, creating a coherent space where both realities can communicate in real-time [14]. A visual representation of the XR continuum is shown in Figure 28.

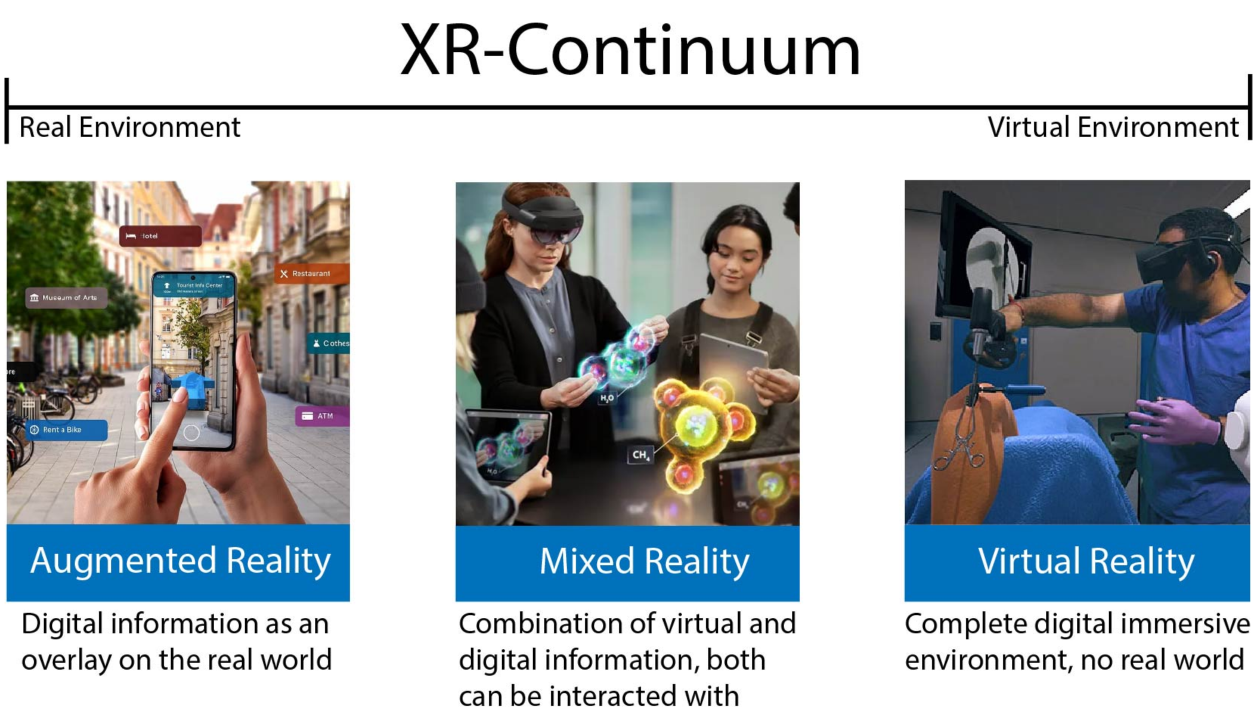

Fig. 28. MR-centered XR Continuum

A.2 AR

Starting from the left side of the spectrum, there is the reality without any virtual elements. Moving to the right, the spectrum starts with AR with very few virtual elements. AR overlays digital elements on the real world with the intent of improving the user experience. These digital elements can be visual, auditory, olfactory, or tactile [6]. It is probable that you already use AR in your daily life with navigation apps like *Google Maps Live View*or photography filters like *Snapchat*. These are examples of using AR on a mobile phone, but other ways are also possible. Think about wearables such as the *Google Glass* or spatial augmented reality that implements AR in the real world, for example, with a projector [7].

AR is occluding the real world partly since it overlays virtual elements on the real world, but still, much of the real world is visible. With the limited occlusion of reality, it is possible to interact with the environment as one would normally, but it may overlay virtual content wrong on real objects, which confuses the user. [66].

Immersion in AR is limited since the user is able to get some virtual content in the real world, but this content lacks spatial capabilities [52].

A.3 MR

Moving more towards the right of the spectrum, we encounter MR. In MR, the virtual components blend more with the environment than in AR, but the real environment is still visible. It tries to place 3D objects in the real world as well as possible [59]. It is also possible to interact with the virtual objects.

MR is very similar to AR in the sense that it can display virtual elements in the real world. The ways of displaying are therefore also very similar to AR, where it is possible to use a handheld device like a phone, use a spatial display, or use a Head-Mounted Display (HMD). Currently, HMDs are the primary choice for achieving the highest level of immersion and natural interaction in MR [52].

MR is occluding the real world in such a way that virtual objects are placed in a room or that a real object is replaced with a virtual object. Still, much of the real world is still visible, and when done correctly, the user would not notice the occlusion too much [66].

The immersion of MR is much better than that of AR since it uses spatial mapping to implement the virtual objects in the real world. If done correctly, it can feel very real and is very immersive [52].

A.4 VR

On the far right of the spectrum is VR. VR completely occludes the real world and only displays virtual elements. This allows the user to become part of the virtual world [71]. Because VR completely occludes the real world, there are many possibilities in comparison to AR and MR. For example, it is possible to trick the brain into thinking it is in a high building to treat height phobia [46]. Typically, it is only possible to interact with virtual objects with handheld or hand-tracking devices because the real world is completely occluded [3].

The first VR environments were displayed on a large screen, where the user was surrounded as much as possible by a screen. Today, HMDs are used mainly to experience virtual reality. This makes the experience better and more immersive, as users can now truly step into virtual worlds and engage with them in a way that wasn't possible with traditional displays. VR is considered the most immersive experience since the user is completely immersed in the virtual environment. Although this has its positive aspects, negative aspects also occur. For example, VR sickness remains a problem when immerged in a virtual environment. One of the triggers of VR sickness is perceived motion in the virtual environment while there is no motion in the real world [75]. Another example is that one can walk into a wall when the virtual environment is not calibrated well.

A.5 Haptics

One of the ways of interacting with the environment in a virtual environment is through haptics. Haptic technology is the field dedicated to integrating touch sensation and control into computer-generated applications. Using haptic devices, people can experience a tactile connection with a virtual environment. Haptic technologies use forces, vibrations, or motions to allow users to interact with a virtual environment by simulating the sense of touch [69]. Although it is also possible to use handheld controllers to control the environment, without haptics, it becomes very difficult to perform basic tasks [30].

The field of haptics was introduced around the 1970s, when research was done in the field of robotics. Researchers found that

Fig. 29. 5 different kinds of haptics; a) Handheld controller b) Desktop haptics *Phantom Desktop Touch* c) Surface haptics device d) Haptic gloves e) Electrotactile feedback device f) Object tracker

making an artificial robot hand was more difficult than expected, making it important to research the field of haptics, but more from a robotic point of view. When computers became more widely available in the early 1990s, the field of haptics tended to communicate with computers[70]. With the rise of computer technology, telerobotics, and virtual reality, haptics became more important [63]. You probably use haptic technology every day; for example, it is used in your phone, indicating that you have a message or making a better gaming experience [15].

In VR, haptics is used to raise the sense of presence [27] and to raise the sense of immersion [58]. Because VR is more widely available nowadays and because it is getting used more and more in areas such as medical and learning applications, it becomes essential to achieve more realism with haptics [19]. The field of haptics can be split into different categories that are elaborated on here.

A.5.1 Handheld devices. The most simple version of haptics are handheld devices (see Figure 29 a). These act more as traditional controllers than as real haptic devices, and the only haptic thing they can do is give vibrotactile feedback. But they are cheap, small, and can be used in a large area [19].

A.5.2 Desktop haptics. Desktop haptics can be compared with a traditional robot arm, but instead of having the arm as the output, it becomes the input. Often, there is a device connected to this device, such as a stylus, that can be moved in 3D space. The arm contains force sensors and actuators to measure forces but also to provide force feedback [19]. Examples of devices that use this principle are the *Haply Inverse3* [1] and the *Phantom Desktop Touch* (see Figure 29 b) [2]. These devices can be used for virtual surgery, product design, assembly of parts, or other virtual projects where tools are needed [18, 19, 23, 64].

A.5.3 Surface haptics. Surface haptics is a kind of haptics that enables a surface to become an active touch surface. It allows users to perceive certain textures or contours on a surface. You can think about a surface having small, adjustable bumps, but you can also think about having vibrations on your mobile phone (see Figure 29 c). Surface haptics can be used in a very broad spectrum, from applications in gaming to eye-free interaction in a car to assisting visually impaired people to read text [19].

A.5.4 Wearable haptics. Then there is also wearable haptics; this is where the haptics device is worn. Think of haptic feedback gloves or even haptic feedback exoskeletons, where forces can be exerted on your body (see Figure 29 d). The biggest difference compared to desktop haptics is that the user can have a large space to interact with. However, these devices can be bulky, heavy, and expensive [19].

A.5.5 Electrotactile feedback. A different field of haptics that has progressed in recent years is electrotactile feedback. This is a subfield of surface haptics but deserves some extra attention since it is new and has promising features. An elaborate systematic review has been done by Kourtesis et al. [40]. Electrotactile feedback is a technology that produces haptic sensations by electrically stimulating nerves in the skin via electrodes placed on the surface of the skin (see Figure 29 e). The biggest advantage of using this kind of feedback is that it is very portable and wearable due to its size and power consumption. Also, the manufacturing costs are low. Most of the research on this topic is done for prosthetic hands and arms, but there is not much research done for VR applications [40]. This field is most valuable where the skin is most sensitive, such as the fingertips and tongue [85]. Research has been done to combine this principle with desktop haptics to make the haptics more precise, but only using electrotactile feedback was not very accurate [72]. This can be trained towards better object discrimination but is still only 50% accurate [4]. Fortunately, research also shows that using this principle in combination with VR is promising, for example, for grasping tasks [33, 35]. There is also evidence that it can give a sense of feeling a force on fingers [80, 84]. New research found that it is even possible to use the electrotactile feedback at the back of the hand, making the front completely usable for other interactions [77].

A.5.6 Real object. The last option for implementing haptics is to introduce a real object with a tracker. This can be done with multiple methods. It is possible to use the stereo cameras of a VR headset to estimate real-life objects and put them in VR. This unfortunately lacks precision since the cameras are not accurate in estimating the objects [60]. Another possibility is by using trackers that can generate the position of an object in 6 dimensions relative to the user. This method is effective although the used devices can be bulky (see: Figure 29 f) [45].

B LEARNING

In this chapter, we dive into what it is to learn a skill, particularly the acquisition of motor skills. We will discuss various aspects of learning, including differences in learning processes and the specific ways in which individuals acquire motor skills.

The term "learning" encompasses a wide range of activities. For instance, one can study a book and learn intellectual skills. Alternatively, one can learn to shoot a football into a goal, thereby developing motor skills. In the field of learning, five main categories are widely accepted [26]:

- Intellectual skills
- Verbal information
- Cognitive strategies
- Motor skills
- Attitudes

All of these skills involve different kinds of learning and have optimal processes. For this research, we will focus on learning motor skills.

B.1 Motor Skills

Motor skill learning is a complex process that involves the acquisition and refinement of movements that require muscle and limb coordination. Unlike intellectual skills, which can be learned abruptly by applying general rules to varied examples, motor skills require repeated practice of the specific movements involved in the task. Motor skill learning is influenced by factors such as feedback, reinforcement, attention, and motivation. According to Fitts and Posner [25], motor skill learning goes through three phases: a cognitive phase, in which the learner acquires the basic procedure or sequence of movements; an associative phase, in which the learner integrates the parts of the skill and improves the smoothness and timing of the movements; and an autonomous phase, in which the learner performs the skill automatically and with minimal attentional demands. Motor skill learning is relevant for many domains of human activity, such as sports, music, writing, driving, and the use of tools [26].

Learning motor skills can be done with various technologies, in various environments, and with a lot of different variables. All these variables should be taken into account when creating a learning environment to optimize transfer. This depends on what should be learned [54]. A problem with training may be that parts of the complete task are learned separately. If the user has mastered all these parts separately and is attempting to complete the task, it can feel overwhelming. Scaffolding offers a solution to this issue. By providing support throughout the learning process, scaffolding ensures that learners experience the complete task rather than isolated parts. This approach helps in integrating and coordinating the various components, mitigating the potential for a learner to feel overwhelmed when performing the task in its entirety [76].

B.2 Learning Methods

There are many learning methods available within the learning sciences. Research shows that two methods work best to learn motor skills: learning through observation and physical practice. Learning through physical practice is more effective, but still, observation also seems to work [82]. Learning motor skills can also be affected by the focus of attention, where the internal focus is less effective than the external focus. Small changes to the instructions can have significant effects. Internal focus is where the focus is on the person, so focus on how the movements of your arms are, for example. External focus can be on, for example, the swing of a golf club. This advantage is significant for everyone (independent of age, gender, and skill level) and also for stressful situations. External focus speeds up the learning process because it focuses on unconscious and automatic processes [82].

During training, it is important to give enough guidance to the user. It was first thought that minimal guidance was ideal for learning, but the opposite is true. Enough guidance should be supplied, while not overwhelming, to guide the user in learning; this improves learning. Guidance can be given through instructions or feedback [37]. This feedback should be chosen carefully since certain ways of giving feedback are more efficient than others. Giving learners the option to get feedback, for example, leads to more efficient learning than always giving feedback [82].

C BUTCHERY

The use case of this study will be butchery. This chapter gives insights into the important tasks of the butcher and how they are done. For this information, an interview was conducted with an expert in the field who is also a teacher at the*SVO vakopleiding food*. The full interview was done in Dutch and can be seen in Appendix D.

A butcher's day-to-day tasks consist of checking the stock, caring for the customers, and, of course, cutting meat. For this chapter we consider having a part of the pig called the ham which is located at the rear of the pig, in a form called the *"vijfde snit"*, which is Dutch and is directly translated as *"fifth cut"*. It means that the product has been fully trimmed; the piece of meat is ready to be sliced. The only thing the butcher has to do at that point is portion it, for example, into 10 schnitzels.

The accuracy of the butcher is very dependent on feeling and skill. Because every piece of meat is different, the butcher should always adapt to what kind of meat he has in front of him. When starting cutting, he should know how many and how thick he wants the meat to be. He should also have the skill of cutting, for example 150 grams of ball steak, because a restaurant requires this amount for every steak. Another thing to consider is that meat should be cut in muscle fibers. These fibres have a certain direction and if cut correctly, the meat will become more tender.

Another important thing is that the butcher mostly cuts with his right hand (or dominant hand), but almost always holds the meat with his left hand. They would say that the left hand is the hand with feeling. If a butcher wants to cut a piece of meat into 10 separate schnitzels, he uses his left hand for two important things; direction and pressure. He uses it to give direction and thickness for the meat, so it is always equally thick. But he also uses the left hand to give pressure on the meat because it will otherwise start to wobble since the meat is not firm. You might even struggle to get your knife through that last piece. So, you need the pressure of your hand to cut the piece in two. An example is shown in Figure 30.

Fig. 30. An example of how meat is cut with both hands.

D EXPERT REVIEW

English version below. The interview was written down in Dutch since the interview was done in Dutch. The English version is translated.

D.1 Introductie

Ik ga onderzoek doen naar hoe wij de ervaring kunnen verbeteren van het slagersvak in virtual reality. Hoe je bijvoorbeeld het slagersvak beter kan leren of hoe je met meer realisme de taken kan uitvoeren. Ik ben pas een aantal weken geleden hiermee gestart dus was helaas de periode daarvoor nog niet betrokken, waardoor ik het een en ander aan informatie heb gemist. Voor mijn eindverslag is het belangrijk om de juiste informatie op te schrijven, vandaar dat ik u een aantal vragen zou willen stellen om het slagersvak beter te kunnen begrijpen.

D.2 Vragen

Vraag 1: **Ik ben erg benieuwd wat het slagersvak precies inhoudt, zou u een korte samenvatting van het takenpakket kunnen geven?** Een slager werkt van begin tot eind, start de dag op, kijkt wat de voorraad is en vervolgens een aantal producten mist in de toonbank. Op basis daarvan begint hij dan met het vlees wat binnengekomen is te snijden zoals hamlappen, varkenslappen en schnitzels. Dus dan begint hij fysiek met het vlees en vult hij zijn toonbank weer. Dat doet hij met varkens-, rund-, en kippenvlees. Daarnaast zijn er vlugklaar artikelen, de halffabrikanten en fabrikanten, die worden ook gevuld. De basis is om te zorgen dat de gasten die binnenkomen een mooi gevulde toonbank zien. Dit wordt gedaan voordat de klanten binnenkomen. Door de dag heen zal hij de toonbank blijven vullen, helpt gasten, doet hand-en-spandiensten om het proces te bevorderen en schoonmaak hoort daar natuurlijk ook bij. Hij doet bestellingen en kijkt wat hij nodig heeft voor de volgende dag of komende dagen. Daarnaast is er ook nog productie zoals worstmakerij en andere zaken die er nog bij komen.

Vraag 2: **Grote stukken vlees komen binnen in de slagerij, hoe begint de slager met dit te snijden door de dag heen?** Er zijn twee types slagers, er zijn slagers die zeggen; op de maandag laat ik heel veel vlees binnenkomen en vacuumeer zodat de producten langer houdbaar zijn. Vervolgens pakt hij het als hij denkt dat hij het nodig heeft, bij een leeg schap of als de klant erom vraagt. En er zijn slagers die, wanneer het vlees binnenkomt, meteen het vlees doorverwerken en ook in het schap leggen. Dus meer zoals het in de supermarkt is waarbij het first in first out principe geldt maar waarbij er wel dagvers wordt verkocht. Dat wilt niet zeggen dat de slager die op maandag alles snijdt en vacuumeerd niet vers genoeg is, het is alleen een andere werkwijze.

Vraag 3: **Wat zijn snijtaken die gedaan moeten worden? Ik kan me voorstellen dat er in 1 keer een groot stuk binnenkomt.** Dit is ook afhankelijk van het bedrijf, we hadden het net al over het verdelen van ham (een process hoe precies een stuk van een varken wordt gesneden). Een aantal bedrijven doen dat wel en een aantal bedrijven die kopen in met de vijfde snit. De vijfde snit betekent dat het product helemaal gevliest is, in feite ligt dan het stuk vlees kant-en-klaar om te snijden. Het enige wat de slager dan nog hoeft te doen is het portioneren in bijvoorbeeld schnitzels en dan haalt hij er bijvoorbeeld 10 schnitzels uit.

Vraag 4: **Hoe nauwkeurig moeten de snedes die de slager doet zijn?** Nu komen we bij het stukje gevoel. Want elk vleesdeel is uniek zou ik zeggen, het heeft wel een basisgewicht, bijvoorbeeld een bovenbil is vaak tussen de 1,3 en 1,6 kilo. En de slager weet precies; ik wil zulke dikke schnitzels of zulke hamlappen hiervan maken en op die manier wordt er dan gesneden. Er is wel een afspraak dat een student, als we het bijvoorbeeld over kogelbiefstuk hebben, dat hij bijvoorbeeld 150 gram kan afsnijden omdat bijvoorbeeld de horeca daarom vraagt. En dat zijn hele gerichte opdrachten die we bij rundvlees bijvoorbeeld wel doen maar bij varkensvlees niet. Want, ik weet niet of je ooit een bovenbil hebt gezien, maar dat bestaat uit vleesdraden. Deze draden lopen in een bepaalde richting en je wilt dan op de draad snijden. Dus dan hoef je maar zo'n klein mogelijk stukje vlees maar hoeft te kauwen in je mond waardoor je niet heel lang hoeft te kauwen. De slager moet soms ook het stuk een beetje draaien omdat de vleesdraden ook een beetje draaien waardoor die dus weer verder gaat, dat is bij de bovenbil het geval. Er zit een deel in wat je liever niet bij mekaar wil hebben dus dan draait de slager het vlees een beetje om dat te ontzien waardoor die dat stukje nog gebruikt voor bijvoorbeeld reepjes vlees van te maken of een ander product.

Vraag 5: **Dat gaat dus echt heel erg om gevoel, over diktes...** Ja precies, je kan niet zeggen, je hebt een bovenbil en we kunnen het allemaal 1 op 1 zo overnemen. Er is natuurlijk wel een gemene deler alleen er zit altijd een soort handeling in, dus de slager kijkt altijd vooral naar de vleesdraad, want dat is dan leidend om een mals product te verkopen.

Vraag 6: **Als je dan kijkt naar het snijden zelf wordt dit met rechts gedaan, ik kan me voorstellen dat je ook veel met je linkerhand bezig bent. Wat doet je linkerhand tijdens het snijden?** Wat een slager altijd doet, dit is eigenlijk je gevoelshand, dus op het moment dat je snijdt komt er bijvoorbeeld een centimeter tussen. En met het gevoel snijdt je met het mes mee (met de uitbeelding van het snijden met rechts en links die plat op het stuk vlees ligt en meebeweegt met het mes). Op het moment dat de slager snijdt, gaat de linkerhand mee, hij begeleidt het lapje zodat het niet op het ene punt dun is en op het andere punt dik. Dus hij bewaart eigenlijk de dikte van het lapje vlees.

Vraag 7: **Dus je moet eigenlijk wel die linkerhand gebruiken om fatsoenlijk te kunnen snijden...** Nee, dit lukt niet. Want wat het vlees doet, dat gaat wiebelen omdat het niet zó stevig is. Op het begin wel maar op het eind houd je een stukje over en dat gaat geheid alle kanten op, je krijgt waarschijnlijk niet eens je mes in dat laatste stukje dan. Dus dan heb je echt de druk van je hand nodig om het lapje in tweeën te snijden.

Vraag 8: **U kent het project met virtual reality, dan zou het wel heel nuttig kunnen zijn als we dat (de linkerhand) voor elkaar krijgen zodat die ook mee kan doen zodat de ervaring rijker wordt...** Klopt, dan wordt hij écht realistich. Ik denk dat studenten al gebaat zouden zijn om te weten welke richting ze op moeten snijden. Ik denk, voor jouw onderzoek, dat het heel handig is die functionaliteit vooral richtinggevend te maken en ook die druk te geven op het product om een gelijkmatig product, consumenteneenheid noemen we het dan, schnitzel of hamlap te maken.

ENGLISH

D.3 Introduction

I am conducting research on how we can improve the experience of the butcher's trade in virtual reality. For example, how one can better learn the butcher's trade or how to perform tasks with more realism. I started this only a few weeks ago, so unfortunately I wasn't involved in the previous period, which means I missed out on some information. For my final report, it is important to write down the correct information, which is why I would like to ask you a few questions to better understand the butcher's trade.

D.4 Questions

Question 1: **I am very curious about what the butcher's trade exactly entails, could you give a brief summary of the tasks involved?** A butcher works from start to finish, starts the day by checking the stock and seeing what products are missing from the display. Based on this, he begins cutting the meat that has arrived, such as pork chops, ham slices, and schnitzels. He physically handles the meat and refills his display case. This includes pork, beef, and chicken. Additionally, there are ready-to-cook items, semi-manufactured and fully manufactured products, which are also stocked. The main goal is to ensure that customers see a well-stocked display case when they enter. This is done before the customers arrive. Throughout the day, he continues to refill the display case, assists customers, performs various tasks to improve the process, and cleaning is naturally part of the job. He places orders and looks at what is needed for the next day or the upcoming days. There is also production work, such as sausage making and other related tasks.

Question 2: **Large pieces of meat arrive at the butcher shop, how does the butcher start cutting these throughout the day?** There are two types of butchers. Some butchers have a lot of meat delivered on Mondays and vacuum-pack it to extend the shelf life. They then use it when they think they need it, such as when a shelf is empty or if a customer requests it. Other butchers process the meat as soon as it arrives and place it directly in the display case, similar to supermarkets where the first-in, first-out principle applies, but with day-fresh products. This doesn't mean that the butcher who cuts and vacuum-packs everything on Monday is not fresh enough; it's just a different method.

Question 3: **What are the cutting tasks that need to be done? I can imagine that large pieces come in all at once.** This depends on the business. We already mentioned dividing ham (a process detailing how a piece of pork is precisely cut). Some businesses do this, while others buy the meat already prepared in the fifth cut. The fifth cut means the product is fully trimmed, ready to be portioned. The only thing the butcher has to do is cut it into portions, such as schnitzels, and he might get, for example, 10 schnitzels out of it.

Question 4: **How precise do the cuts made by the butcher need to be?** Now we get to the part about precision. Each piece of meat is unique, I would say. It has a standard weight, for example, a top round typically weighs between 1.3 and

1.6 kilos. The butcher knows exactly; I want such thick schnitzels or such thick ham slices from it, and that's how it's cut. There is an agreement that a student, when we talk about eye fillet, for example, can cut 150 grams because, for instance, the catering industry requires it. These are specific tasks we do with beef but not with pork. If you've ever seen a top round, it consists of meat fibers that run in a specific direction, and you want to cut with the grain to ensure that you have the smallest possible piece of meat to chew, minimizing chewing time. The butcher sometimes needs to turn the piece because the meat fibers also twist, and that's the case with the top round. There's a part you'd prefer not to keep together, so the butcher twists the meat a bit to avoid that, using the remaining part for strips of meat or another product.

Question 5: **So it's really about the feel, the thickness...** Exactly, you can't say, you have a top round, and we can cut it all the same. There is a general guideline, but there is always some manual handling involved, so the butcher always looks mainly at the meat fiber, as this is crucial to selling a tender product.

Question 6: **When you look at the actual cutting, it is done with the right hand, but I can imagine you also use your left hand a lot. What does your left hand do during the cutting?** What a butcher always does, this is your guiding hand, so when you cut, for instance, there might be a centimeter between cuts. You guide the knife with your feeling hand (mimicking the cutting motion with the right hand while the left hand is flat on the meat and moves with the knife). When the butcher cuts, the left hand follows, guiding the meat to ensure it's not thick in one spot and thin in another. Essentially, it maintains the thickness of the piece of meat.

Question 7: **So you really need to use your left hand to cut properly...** No, it won't work without it. Because what happens to the meat, it wobbles as it isn't that firm. In the beginning, yes, but towards the end, you are left with a piece that will certainly move in all directions, and you probably won't even get your knife into that last piece. So you really need the pressure from your hand to cut the piece of meat in two.

Question 8: **You know the project with virtual reality, it could be very useful if we could include (the left hand) to enrich the experience...** Exactly, then it becomes really realistic. I think students would benefit from knowing which direction to cut in. I think for your research, it would be very useful to make that functionality directional and also to apply pressure to the product to create an even product, what we call a consumer unit, schnitzel, or ham slice.

E GJK ALGORITHM

E.1 Introduction

The Gilbert-Johnson-Keerthi (GJK) algorithm is a well-known algorithm in computational geometry, it applied to determine the distance between two convex objects. For most physics engines, GJK is extensively used in collision detection. This is particularly useful for video game and simulation implementations where complex convex shapes and objects can collide with each other.

E.2 Description of Algorithm

The GJK algorithm uses an iterative method. It refines a set of points known as a simplex to get closer to the shortest distance between two convex shapes. If this distance becomes zero, the shapes are colliding. The algorithm contains out of several key steps:

- **Initialization** It selects an initial search direction and calculates support points.
- **Simplex Construction** Iteratively adding points to the simplex to better approximate the shortest distance between the shapes.
- **Termination** Determining whether the shapes are colliding or whether you have found the closest distance between the shapes.

E.3 Detailed Steps

E.3.1 Initialization. The algorithm starts by choosing an initial direction, typically towards the origin from an arbitrary point on one of the shapes, but this direction does not really matter. The support function is then used to find the furthest points in this direction for both shapes and compute their difference.

E.3.2 Simplex construction. The algorithm enters a loop that continuously refines the simplex. For each iteration, it adds a new support point to the simplex and checks if that point advances toward the origin. In this case, if the new point does not go nearer to the origin, this implies the two shapes are not colliding; otherwise, update the simplex and refine the direction.

E.3.3 Direction Update and Simplex Refinement. For the simplex construction in 3D we use a tetrahedron, the tetrahedron is used with a simplex of 4 points. A tetrahedron is a type of polyhedron that has four triangular faces. It is one of the simplest three-dimensional shapes and is a type of pyramid with a triangular base. But the algorithm always starts with a line and than progresses towards more advanced shapes (triangle, tetrahedron).

E.3.4 Line Handling. For a line segment, the algorithm checks the direction between the points and adjusts the search direction perpendicular to this line towards the origin.

E.3.5 Triangle Handling. For a triangle, the algorithm checks the normal vectors to the triangle's edges and determines if the origin lies within the plane formed by the triangle. Depending on the result, the simplex is refined to a line segment or kept as a triangle with an updated direction.

E.3.6 Tetrahedron Handling. For a tetrahedron, the algorithm examines the faces of the tetrahedron to determine if the origin lies within it. If the origin is found to be inside the tetrahedron, a collision is detected. Otherwise, the simplex is reduced to a triangle, and the direction is updated.

E.4 Termination Condition

The algorithm terminates when the simplex encloses the origin, indicating a collision, or when the maximum number of iterations is reached, suggesting no collision.

E.5 Supporting Functions

These are all the supporting functions that are used to calculate everything.

E.5.1 Support Function. The support function calculates the furthest point in a given direction from the Minkowski Difference of the two shapes. This involves finding the points in each shape that are furthest along the direction vector and subtracting one from the other.

E.5.2 Furthest Point Calculation. To find the furthest point in a shape along a given direction, the algorithm uses the dot product to determine which point has the maximum projection in that direction.

E.5.3 Direction Check. A helper function checks if two vectors are pointing in the same general direction by using the dot product. This ensures that the search direction is adjusted correctly towards the origin.

E.6 Pseudocode

Algorithm 1 GJK Collision Detection Algorithm

```
function GJKCollision(vertices1, vertices2, direction)
    # Initialize the simplex as an empty list
    simplex ← empty list
    # Find the first support point in the given direction
    support ← Support(vertices1, vertices2, direction)
    # Add the first support point to the simplex
    Insert support to the simplex
    # Set the next direction towards the origin
    direction ← −normalize(support)
    # Loop for a maximum of 100 iterations
    for i = 0 to 99 do
        # Find the next support point in the current direction
        support ← Support(vertices1, vertices2, direction)
        # Add the new support point to the simplex
        Insert support to the simplex
        # Check if the new support point did not pass the origin
        if dot_product(support, direction) ≤ 0 then
            # If it didn't pass the origin, there is no collision
            return false
        end if
        # Update the simplex and direction based on the current simplex configuration
        if NextSimplex(simplex, direction) then
            # If the simplex contains the origin, there is a collision
            return true
        end if
        # If the loop ends without detecting a collision, return false
    end for
    return false
end function
```

F EPA ALGORITHM

F.1 Introduction

The Expanding Polytope Algorithm (EPA) is used for computational geometry and physics engines. The Expanding Polytope Algorithm is applied in such instances as to find the penetration depth and direction between the two intersecting convex shapes. This chapter outlines the EPA algorithm and its implementation.

F.2 Overview

EPA starts with a polytope derived from the result of the GJK (Gilbert-Johnson-Keerthi) algorithm, which detects collisions between two convex shapes. EPA then refines this polytope iteratively to find the closest face to the origin along the polytope's surface, determining the penetration depth and direction.

F.3 Detailed Explanation

F.3.1 Initialization. Setup an initial polytope and list of faces. The polytope is a container for vertices defining the simplex, we will use a tetrahedron because we work in 3D. The normal vectors of all faces of the polytope are computed, and the face that is closest to the origin is found.

F.4 Face Normals Calculation

The normal vectors to every face are calculated by the vector cross product of two edges of a triangular face, followed by its normalization. The algorithm keeps track of the face with the smallest distance to the origin.

F.4.1 Iteration.

Support Point Calculation. The algorithm calculates a support point in the direction of the normal vector of the closest face. This support point is the farthest point on the combined shapes in the given direction.

Face Removal and New Faces Addition. It removes all faces that are visible from the newly computed support point. It adds new faces that are formed by these unique edges and the support point into the polytope.

Convergence Check. The algorithm checks the distance from the new support point to the origin and compares it to the minimum distance previously found. If the change in distance is below a certain threshold, the algorithm stops, indicating convergence.

Penetration Vector. The normal vector of the closest face, scaled by the minimum distance, is returned. This vector represents the direction and magnitude of penetration between the two shapes.

F.5 Pseudocode

Algorithm 2 EPA (Expanding Polytope Algorithm)

```
function EPA(vertices1, vertices2, direction, polytope)
    # Initialize faces of the polytope using a list of indices representing triangles
    faces ← [0, 1, 2, 0, 3, 1, 0, 2, 3, 1, 3, 2]

    # Calculate initial face normals and find the index of the face with minimum distance to the origin
    faceNormals, minFace ← GetFaceNormals(polytope, faces)

    # Initialize the variables to hold the normal and distance of the closest face
    minFaceNormal ← (0, 0, 0) # Placeholder for the normal of the closest face
    minDistance ← ∞ # Set initial minimum distance to a large number (infinity)

    # Loop until the minimum distance is updated
    while minDistance = ∞ do
        # Get the normal vector of the face closest to the origin
        minFaceNormal ← faceNormals[minFace][0 : 3]

        # Get the distance from the origin to the closest face
        minDistance ← faceNormals[minFace][3]

        # Calculate the support point in the direction of the closest face's normal
        support ← Support(vertices1, vertices2, minFaceNormal)

        # Calculate the distance of the support point along the direction of minFaceNormal
        sDistance ← dot(support, minFaceNormal)

        # Check if the difference between sDistance and minDistance is significant
        if |sDistance − minDistance| > 0.001 then # Continue expanding the polytope if the distance difference is above the threshold
            # Reset minDistance to infinity and initialize an empty list for unique edges
            minDistance ← ∞
            uniqueEdges ← empty list

            # Iterate through all face normals
            for i = 0 to length(faceNormals) − 1 do
                # Check if face is visible from the support point
                if dot(faceNormals[i][0 : 3], support) > dot(faceNormals[i][0 : 3], polytope[faces[i × 3]]) then
                    # Get the starting index of the current face in the faces list
                    f ← i × 3
                    # Add unique edges from the current face
                    AddIfUniqueEdge(uniqueEdges, faces, f, f + 1) # Add edge (f, f+1) if unique
                    AddIfUniqueEdge(uniqueEdges, faces, f + 1, f + 2) # Add edge (f+1, f+2) if unique
                    AddIfUniqueEdge(uniqueEdges, faces, f + 2, f) # Add edge (f+2, f) if unique

                    # Remove the current face and its corresponding normal from the lists
                    RemoveFace(faces, faceNormals, i)

                    # Adjust index due to the removal of a face
                    i ← i − 1
                end if
            end for
            # Initialize a list to hold the indices of the new faces to be created
            newFaces ← empty list

            # Iterate over all unique edges
            for edge ∈ uniqueEdges do
                # Create new triangles from each unique edge and the support point
                newFaces.append(edge[0])
                newFaces.append(edge[1])
                newFaces.append(length(polytope)) # Index of the new vertex (support point)
            end for
            # Add the support point to the polytope as a new vertex
            polytope.append(support)

            # Calculate new face normals and update the index of the face with the minimum distance
            newNormals, newMinFace ← GetFaceNormals(polytope, newFaces)
            minFace ← UpdateMinFace(faceNormals, newNormals, minFace, newMinFace)

            # Add the new faces and their normals to the existing lists
            faces.extend(newFaces)
            faceNormals.extend(newNormals)
        end if
    end while
    # Return the penetration vector by scaling the minimum face normal by its distance to the origin
    return minFaceNormal × minDistance
end function
```

G FEEDBACK IDEATION

This appendix contains some information about the used programs, versions, amount of scripts, and amount of lines. The programmes that are used are *Unity (2022.3.19f1)* and *Arduino IDE (2.3.2)*. The amount of scripts and lines written in these programmes are shown in Table 7. The packages used in *Unity* are:

- Haply Inverse for Unity
- PICO Integration
- PICO Live Preview
- XR Interaction Toolkit
- XR Plugin Management
- Mobile Gastronomic Kitchen Props
- Uduino
- World Materials Free

Program	**Script**	**# of lines**
Unity		
	ArduinoController	45
	DeformRibeye	90
	DontDestroy	10
	GJKOnDevice	1048
	ObjectPlayback	224
	ObjectRecorder	134
	PersistentObject	21
	StartupSceneController	56
	OverlayUI	299
	VROverlayUI	95
	Total	2022
Arduino		
	ArduinoScriptPhysicalMeat	79
	Total	79
Total		2101

Table 7. Script and Lines Count

H SIMPLE FEEDBACK EXPLANATION

Need for Feedback

- **Essential**: Athletes are unable to learn without feedback about their performance.
- **Facilitative**: Feedback can facilitate motor learning; athletes can learn particular skills without feedback, but their learning curve is steepened by providing feedback.
- **Non-essential**: Feedback can be inessential to motor learning; athletes can learn a skill just as well with or without feedback.
- **Hindrance**: Feedback can hinder motor learning; athletes learn a particular skill better or faster without feedback.

Timing

- **Internal focus**: With instruction on how something is performed by a professional, feedback that directs the attention of the learner towards the movement itself facilitates an 'internal focus of attention'.
- **External focus**: With instruction on how something is performed by a professional, focusing on the effect of the action.
- **Self-modelling**: Involves the learner observing their own performance through techniques such as video recordings, real-time feedback, or reflective practices.
- **Learner-modelling**: Involves observing and learning from peers or other learners at a similar proficiency level.
- **Expert-modelling**: Involves observing and learning from individuals who are highly proficient or skilled in a particular area.
- **Concurrent feedback**: The learner receives feedback during the execution of the action.
- **Guidance**: The (often physical) constraining of motor error, typically by an instructor, during movement execution.
- **Immediate terminal feedback**: The learner receives feedback directly after the execution of the action.
- **KR/KP-delay interval**: The learner receives feedback when an action is completed or the result of the action is known.
- **Post KR/KP-delay interval**: The delay after receiving feedback, as time is needed to learn from actions and feedback before performing the action again.
- **Inter-response interval**: Total time between successive attempts, encompassing the delay intervals and feedback processing.

Modality

- **Abstract Visualizations**: Use of non-realistic or symbolic representations to provide feedback, such as graphs or diagrams showing performance metrics.
- **Abstract Mapping**: Visual representations that link abstract data to the learner's performance, like heat maps showing areas of activity.
- **Realistic Visualizations**: Feedback provided through realistic images or videos, such as video playback of the learner's performance.
- **Loudness**: The volume of feedback, which can vary to emphasize certain aspects of performance.
- **Pitch**: The frequency of the sound used in feedback, which can convey different types of information.
- **Timbre**: The quality or color of the sound, which can make feedback more distinct or meaningful.
- **Timing**: The timing of auditory feedback, ensuring it is synchronized with the performance.
- **Rhythm**: The pattern of sounds, which can be used to guide the timing of movements.
- **Localization**: The direction from which the sound comes, helping to spatially orient the learner.
- **Reverberation**: The echo quality of the sound, which can add depth to the auditory feedback.
- **Spatialization**: The placement of sound in three-dimensional space to provide more immersive feedback.
- **Placement**: The location on the body where haptic feedback is applied.
- **Number of Actuators**: The number of points at which haptic feedback is delivered.
- **Frequency**: The rate at which haptic feedback is delivered.
- **Intensity**: The strength of the haptic feedback.

- **Patterning**: The sequence and pattern of haptic feedback.
- **Kinesthetic**: Feedback related to the sensation of movement and position, providing a sense of motion or force.
- **Audio–Visual**: Combining auditory and visual feedback.
- **Audio–Haptic**: Combining auditory and haptic feedback.
- **Visual–Haptic**: Using visual and haptic feedback.
- **Audio–Visual–Haptic**: Integrating all three modalities to create an immersive and highly informative feedback system.

Frequency

- **Fading**: Gradually reducing the frequency of feedback as the learner becomes more proficient.
- **Bandwidth**: Providing feedback only when performance deviates beyond a certain range of acceptable performance.
- **Self-selection**: Allowing learners to request feedback when they feel it is necessary.
- **Average**: Giving feedback based on the average performance over a series of trials.
- **Summary**: Providing feedback that summarizes performance over a set period or number of trials.

Content

- **Knowledge of Performance (KP)**: Information about the movement pattern or technique used in performing the action.
- **Knowledge of Results (KR)**: Information about the outcome of the action, such as whether a goal was achieved.
- **Quantitative**: Feedback that provides numerical or measurable information about performance.
- **Qualitative**: Descriptive feedback that provides insights into the quality or nature of the performance.
- **Single Error Response**: Feedback that focuses on one specific error made during performance.
- **Multi Error Response**: Feedback that addresses multiple errors or aspects of performance in a single session.
- **Prescriptive**: Feedback that provides specific instructions on how to correct errors.
- **Descriptive**: Feedback that describes what was done correctly or incorrectly without providing specific correction instructions.
- **What Went Right**: Feedback focusing on successful aspects of the performance to reinforce correct actions.
- **What Went Wrong**: Feedback focusing on errors or aspects that need improvement to guide correction.
- **Internal**: Feedback related to the movement itself, such as body positioning or technique.
- **External**: Feedback related to the effects of the movement on the environment, such as the outcome or impact of the action.
- **Correct**: Providing accurate and truthful information about the performance.
- **Erroneous**: Providing inaccurate information, sometimes used deliberately to test the learner’s ability to self-correct.

I BUTCHER INTERVIEW 2

I.1 Cutting a Ribeye

Cutting a ribeye is similar to cutting a ham slice or schnitzel. The difference lies in the firmness of the meat; beef is generally stiffer and thus more challenging to cut through. Additionally, for a ribeye specifically, the top part is slightly tougher to cut through, which could potentially be simulated in Unity for added realism.

I.2 Standard Meat Cutting Technique

The usual method of cutting meat involves observing the fibers within the meat. The butcher then cuts perpendicular to these fibers to ensure they are properly severed, making the meat less chewy.

I.3 Silicone Simulation

The silicone currently used approximates the feel of a piece of meat. It is not exactly the same as a ribeye but is a good average representation of meat texture. This can be effectively used, especially when combined with VR, which can trick the brain to some extent. It should be noted, however, that meat typically feels cooler and wetter, which could potentially be simulated if feasible.

I.4 Estimating Meat Thickness

An important aspect that I forgot to mention is the estimation of meat thickness. Students should be able to cut slices that are 1.5 or 2 cm thick, for example.

I.5 Flexibility of Meat

One should consider that a piece of ribeye is quite flexible, comparable to the flexibility of your biceps.

I.6 Task Objective

The goal is to perform cutting movements efficiently. The objective also includes achieving the correct thickness of the meat. Fewer cutting movements result in a better and straighter cut.

I.7 Future Perspective

While cutting, one might encounter something more challenging to cut through, such as a bone, veins, or other elements. This is not important for this research initially but is good to keep in mind.

I.8 Learning Objectives

All are important, so determining the 1.5 cm thickness is necessary. The four aspects (straight cutting, fewer cutting movements, determining thickness, applying pressure on the side of the meat) ultimately lead to cutting with a uniform thickness. This makes all learning objectives equally important.

I.9 Parameters

- **Number of Cutting Movements:** Important, for ribeye, a maximum of 3.
- **Percentage of Meat Deformation:** Important, it should not deform; otherwise, the final piece will be more curved.
- **Orientation:** Important to have your knife straight before you start cutting.
- **Orientation Change:** Not necessarily important; the focus is more on ensuring the cut is straight, which can also be influenced by other factors.
- **Pressure:** Important, do not apply too much pressure. Students often apply too much pressure, but speed is more crucial, similar to sawing.
- **Speed:** Important.
- **Recording the Entire Movement:** Useful for calculating everything and can be used so that a professional (recorded) cut can be played back as an example.
- **Time:** Doesn't matter; quality is important.

- **Consistency Across Multiple Cuts:** Important, this is also what happens normally in practicals, where evaluations are done over the past 5 or 6 cuts. This can be achieved by creating 3D models with a certain deformation to make this visible and to determine flatness. The more pressure you apply to the knife, the more likely errors will occur, but you can apply counter-pressure for this.
- **Meat Deformation:** Important! The bulge currently being created is actually unrealistic; in meat, it is more likely to appear mainly at the bottom because the meat is pressed against the table. Moreover, the further you progress in the cut, the less pressure affects the bulge, and this bulge eventually disappears in the final part.

I.10 Feedback

When is feedback typically given: before, during, or after? Often, instructions are given beforehand with a demo; even in the workplace, this is done by the head butcher who demonstrates it once. Then the students start cutting themselves, and for beginners, a lot of feedback is given during the cutting to ensure it is done safely and better. It is always evaluated afterwards to show the student the difference between the various slices and what went wrong. As they become better, they are allowed to work more independently, and evaluation is only done afterwards. Several aspects are therefore important here:

I.11 Everyone

- **Timing beforehand** with visual guidance focused on how the task goes with external attention, performance.
- **Timing afterwards**, after several times, visually looking at what you have done, externally, performance, quantitative, prescriptive.

I.12 Beginners

- **Timing during** with a focus on safety, ensuring that the pinky does not get under the meat (internal attention), audio feedback, if it goes badly, the result, quantitative or qualitative to stop immediately for safety, prescriptive.

I.13 Intermediate

- **Timing during**, audio, if it goes badly, focused on the straightness of the cut (external), performance, quantitative, prescriptive.

I.14 Additional Notes

I.14.1 Can You Apply Too Much Pressure with Your Left Hand? Does the Meat Deform to the Other Side? Initially, a little bit at the top of the meat; this is very noticeable during cutting, so it doesn't go wrong quickly. If you apply even more pressure, the meat shifts, so there's no problem with deformation.

I.14.2 Do You Normally Feel the Movement in the Cutting Direction of the Meat? How Does This Work in Real Life? Not really, except for the very last part you cut from the larger piece. Not relevant for now.

I.14.3 Is This Knife Normally Used for These Applications? Yes.

I.14.4 How Does the Deformation of the Physical Mock Meat Feel? Good, the pressure you need to apply seems realistic on average. However, it normally deforms only at the bottom. The springiness is thus applied in a good way.

J INFORMATION LETTER AND CONSENT FORM

Informatiebrief

Auteur: Dieuwert Wolters
Laatst bewerkt: 03-06-2024

Deze informatiebrief is opgesteld om de deelnemer te informeren over dit onderzoek dat gericht is op het verbeteren van leeromgevingen binnen het vakgebied van vlees snijden. Jouw inzichten en feedback zijn van onschatbare waarde voor ons, omdat we streven naar een beter begrip van de dynamiek van dit leerproces en naar verbetering van de methoden van feedback die aan de leerlingen worden gegeven. Tijdens de sessie, die ongeveer 10 minuten zal duren, zullen we een experiment uitvoeren waarbij je de leeromgeving van een slagerij in VR zult ervaren. Je zult dan het vlees snijden in VR met een nep mes in je hand en in je andere hand een nep stuk vlees. Je zult alles ervaren alsof je vlees snijdt in de echte wereld, maar je krijgt extra feedback. Daarna zal ik je vragen stellen over hoe je deze leerervaring ervaart om meer inzicht in het onderwerp te krijgen. Ook zullen je handelingen in VR worden opgenomen zodat we je resultaten kunnen vergelijken met andere resultaten en daaruit conclusies kunnen trekken. Er zullen geen persoonlijke gegevens worden verzameld, alleen die van het toestemmingsformulier, dat niet openbaar wordt gemaakt en veilig wordt bewaard aan de Universiteit Twente.
Het is belangrijk op te merken dat jouw deelname geen inherente risico's met zich meebrengt, en het onderzoeksproject is grondig beoordeeld door de Ethische Commissie Informatie- en Computertechnologie om te zorgen voor naleving van ethische normen. Jouw deelname aan dit onderzoek is volledig vrijwillig, en je bent vrij om op elk moment zonder straf of consequenties terug te trekken. Er worden geen persoonlijke gegevens verzameld tijdens de studie.
De inzichten die worden verzameld uit jouw deelname zullen worden gebruikt voor de doeleinden van dit onderzoeksproject en kunnen ook bijdragen aan toekomstige studies op dit gebied. Jouw bijdragen zullen naar behoren worden opgemerkt en kunnen worden opgenomen in onderzoeksrapporten en publicaties. Als je vragen of zorgen hebt over jouw deelname, aarzel dan niet om contact met ons op te nemen via de contactgegevens onderaan deze pagina. We waarderen je hulp en kijken uit naar de samenwerking om meer te begrijpen van het snijden van vlees om het onderwijs te bevorderen.

Bedankt voor je tijd en hulp.

Researcher: Dieuwert Wolters: D.wolters@student.utwente.nl
Supervisor: Dennis Reidsma: D.reidsma@utwente.nl
Ethics committee: Ethicscommittee-CIS@utwente.nl
Dynteq: info@dynteq.nl

UNIVERSITY OF TWENTE.

Toestemmingsformulier voor Slagerservaring in VR

U krijgt een kopie van dit toestemmingsformulier

Gelieve de juiste vakjes aan te kruisen	Ja	Nee	
Deelname aan het onderzoek			
Ik heb de studie-informatie van [17/06/2024] gelezen en begrepen, of het is aan mij voorgelezen. Ik heb vragen kunnen stellen over het onderzoek en mijn vragen zijn naar tevredenheid beantwoord.	O	O	
Ik geef vrijwillig toestemming om deel te nemen aan dit onderzoek en begrijp dat ik vragen mag weigeren te beantwoorden en dat ik op elk moment zonder reden mag stoppen met het onderzoek.	O	O	
Ik begrijp dat deelname aan het onderzoek inhoudt dat ik een prototype test waarbij mijn bewegingen worden opgenomen en dat ik interviewvragen beantwoord die door de onderzoeker worden genoteerd.	O	O	
Gebruik van de informatie in het onderzoek			
Ik begrijp dat de informatie die ik geef, wordt gebruikt voor het onderzoeksrapport en de presentatie. Deze zullen openbaar beschikbaar zijn.	O	O	
Ik begrijp dat persoonlijke informatie over mij die mij kan identificeren, zoals mijn naam of waar ik woon, niet buiten het onderzoeksteam zal worden gedeeld.	O	O	
Toekomstig gebruik en hergebruik van de informatie door anderen			
Ik geef toestemming voor het archiveren van mijn anonieme antwoorden uit het interview in de Dynteq-database, zodat deze kunnen worden gebruikt voor toekomstig onderzoek en leren.	O	O	
Ik geef toestemming voor het archiveren van mijn anonieme opgenomen bewegingen in de Dynteq-database, zodat deze kunnen worden gebruikt voor toekomstig onderzoek en leren.	O	O	
Handtekeningen			
______________________ ______________________ ________ Naam deelnemer Handtekening Datum			
Ik heb de informatieblad nauwkeurig voorgelezen aan de potentiële deelnemer en naar beste kunnen ervoor gezorgd dat de deelnemer begrijpt waarvoor hij/zij vrijelijk toestemming geeft. Dieuwert Wolters ______________________ ________ Naam onderzoeker Handtekening Datum			
Contactgegevens voor verdere informatie: **Dieuwert Wolters** **d.wolters@student.utwente.nl** **Contactinformatie voor vragen over uw rechten als onderzoeksdeelnemer** Als u vragen heeft over uw rechten als onderzoeksdeelnemer of informatie wilt verkrijgen, vragen wilt stellen of eventuele zorgen over dit onderzoek wilt bespreken met iemand anders dan de onderzoeker(s), neem dan contact op met de secretaris van de Ethische Commissie van CIS aan de Universiteit Twente via Ethicscommittee-CIS@utwente.nl.			

UNIVERSITY OF TWENTE.

K STUDENT TESTING PROCEDURE

GROUP 1: FIRST ONLY RIGHT HAND

Introduction

You will soon put on a Virtual Reality (VR) headset. You will find yourself in a virtual butcher shop where you see a piece of meat and a knife. With this simulation, we want to investigate and improve your cutting experience.

Initial Setup

When you put on the VR headset, you will initially see nothing. Once I press a button, you will be transported to the butcher shop. In front of you is a piece of meat, and next to you is a knife that you can use. First, an instructional video from the butcher will be played so that you know exactly how to cut.

Putting on the VR Headset

You can now put on the VR headset. If the image is not completely sharp, you can adjust the lenses a bit on the inside of the headset until you are satisfied. Do not touch the lenses themselves...

Activate Play Expert

First Task

Your first task is to cut the meat along the indicated cut line as you would normally do with only your cutting hand. You can try this once to feel how it is to cut, and then perform the action three times. During this task, you are not allowed to use your left hand. Each time, I will indicate that you can start cutting again.

Toggle force on, practice first

After practice → Again + Record (3 times)

Second Task

Now we will involve your left hand. You can use it to hold and feel the piece of meat. You will notice that the meat deforms when you apply pressure to it. The additional task is to counteract this deformation with your left hand. Now cut three more times, using both your right hand and your left hand. After the three cuts, your progress will be shown in numbers from 1 to 10.

Feedback on

Again + Record (3 times)

I will now turn off the simulation.

GROUP 2: FIRST BOTH HANDS

Introduction

You will soon put on a Virtual Reality (VR) headset. You will find yourself in a virtual butcher shop where you see a piece of meat and a knife. With this simulation, we want to investigate and improve your cutting experience.

Initial Setup

When you put on the VR headset, you will initially see nothing. Once I press a button, you will be transported to the butcher shop. In front of you is a piece of meat, and next to you is a knife that you can use. First, an instructional video from the butcher will be played so that you know exactly how to cut.

Putting on the VR Headset

You can now put on the VR headset. If the image is not completely sharp, you can adjust the lenses a bit on the inside of the headset until you are satisfied.

Activate Play Expert

First Task

Your first task is to cut the meat along the indicated cut line as you would normally do with both hands. The right hand will be the cutting hand, and the left hand will be placed against the meat. You will notice that the meat deforms when you apply pressure to it. The task is to counteract this deformation with your left hand. Now cut three times, using both your right hand and your left hand. After the three cuts, your progress will be shown in numbers from 1 to 10. You can try this once to feel how it is to cut, and then perform the action three times. Each time, I will indicate that you can start cutting again.

Toggle force on, practice first

After practice → Feedback on

Again + Record (3 times)

Second Task

Your second task is to cut the meat along the indicated cut line as you would normally do with only your cutting hand, so you are no longer allowed to use your left hand. Each time, I will indicate that you can start cutting again.

Feedback off

Again + Record (3 times)

I will now turn off the simulation.

L INTERVIEW QUESTIONS AND QUESTIONNAIRE STUDENTS

L.1 Interview

1. **What did you think of it?**

   ____

2. **How did the cutting motion feel during slicing?**

   ____

3. **How did this cutting motion differ from cutting real meat?**

   ____

4. **How did you experience using only the knife for cutting?**

   ____

5. **How did you feel using your left hand during cutting?**

   ____

6. **How did the meat feel to you? And the deformation of the meat?**

   ____

7. **How important did you find the posture and position of your body during cutting?**

   ____

8. **What did you think of the feedback you received while learning to cut, and how did it influence your actions?**

   ____

9. **What would you change about the VR environment to improve your cutting experience?**

   ____

10. **Do you have any further comments you would like to note?**

    ____

L.2 Questionnaire

Answer the following questions:

a. **How realistic did you find the cutting experience in VR?**
   Not at all realistic Not realistic Neutral Realistic Very realistic
   ○ ○ ○ ○ ○

b. **How did cutting with the knife feel?**
   Not at all realistic Not realistic Neutral Realistic Very realistic
   ○ ○ ○ ○ ○

c. **How did the meat feel in texture and deformation?**
   Not at all realistic Not realistic Neutral Realistic Very realistic
   ○ ○ ○ ○ ○

d. **How important was the visual feedback to your cutting experience?**
   Not important at all Not important Neutral Important Very important
   ○ ○ ○ ○ ○

e. **How effective did you find the VR environment for learning cutting techniques?**
   Not effective at all Not effective Neutral Effective Very effective
   ○ ○ ○ ○ ○

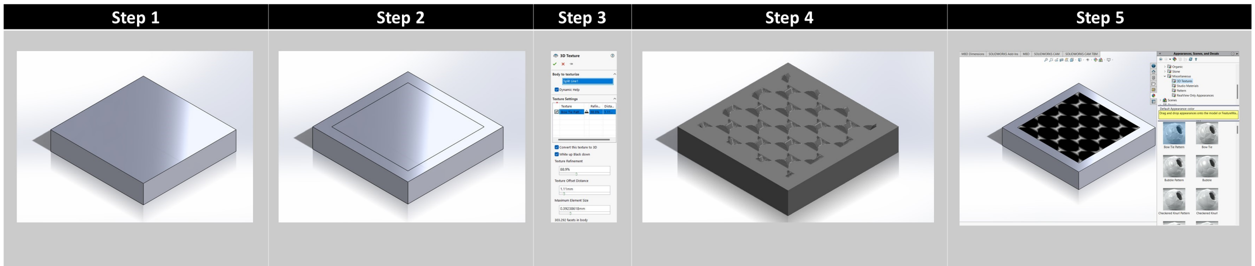

Fig. 31. SolidWorks 3D texture steps

M SOLIDWORKS 3D TEXTURE

In SolidWorks it is possible to create any texture on a surface with a black and white image. This process is described in this appendix.

- Step 1: Create the body or surface that you want to have a 3D texture on. Watch out: A 3D texture will change your body into a Graphic Body.
- Step 2: If you want to only apply the texture to a certain part of the surface, create a sketch and use the Features>Curves>Split Line feature to split the surface.
- Step 3: Change the appearance of the surface with a custom texture, you can choose from the Appearance library (Appearances(color)>Miscellaneous>3D Textures) or import your own black and white appearance image.
- Step 4: Apply the 3D texture feature (Insert>Features>3D Texture) and change the settings according to your preferences.
- Step 5: You now have a texture on your model, it is always possible to remove the feature to go back to the original part or change any parameters.