UNIVERSITY OF GENOA

MASTER'S PROGRAM IN BIOENGINEERING

Thesis submitted in partial fulfilment of the requirements for the title of
Master of Bioengineering

Natural Grasping is not Precision Grip

Fabrizio Lepori

07/23

Thesis advisor: Prof. Manuela Chessa
Thesis co-advisor: Dott. Guido Maiello
Prof. Roland W. Fleming

Contents

Contents 2

Abstract 4

Chapter 1: **INTRODUCTION** 5

1.1. Literature review 6

1.1.1. Precision vs multi-digit grip 6

1.1.2. Influence of objects features. 9

1.1.3. Grasping in Virtual and Augmented Reality 15

1.2. Objectives 16

1.2.1. Is unconstrained grasping precision grip? 16

1.2.2. Do material composition and grip technique influence grasping? 17

1.2.3. Is material composition the primary determinant factor in visually guided grasping? 18

1.2.4. Development of a co-registration method for the alignment of real and virtual objects. 19

1.3. Thesis motivation 20

Chapter 2: **METHODS AND MATERIALS** 22

2.1. Participants 22

2.2. Apparatus 22

2.3. Stimuli 24

2.4. Procedure 25

2.4.1. Training session 25

2.4.2. Unconstrained session 26

2.4.3. Precision grip session 27

Chapter 3: **ANALYSIS** 28

3.1. Roto-translating the objects to their correct position in the *MATLAB* environment. 28

3.2. Estimation of frame of first contact between thumb, index finger and object during precision grip 30

3.3. Estimation of first contact between fingers and object for unconstrained grasps. 32

3.4. Manual evaluation 33

3.5. Identification of the contact points on the object 33

3.5.1. Estimation of number of fingers in contact with the object for the unconstrained grasps. 34

3.5.2. Estimation of center of contact points ("grasp centroid"). 35

3.6. Co-registration of real and virtual objects 35
Chapter 4: **RESULTS** **38**
4.1. In unconstrained conditions participants rarely employ just two fingers. 39
4.2. Material composition and Grip Technique have an impact on grasping behaviour. 41
4.2.1. Material composition has an impact on both precision and multi-digit grasping. 42
4.2.2. Grip technique impacts grasping. 44
4.3. Material composition is not the primary determinant factor in grasping. 47
4.3.1. Reach distance plays a bigger role than material composition in grasping. 48
4.3.2. The same effect is consistent in both precision and unconstrained grip. 49
4.4. Evaluation of the co-registration method 51
Chapter 5: **DISCUSSION** **54**
5.1. Precision Grip is not the natural grip. 54
5.2. Material composition affects both precision and unconstrained grasping but not as the primary determinant factor. 56
5.3. Co-registration of Real and Virtual footage 58
5.4. Potential further applications in various sectors 60
Chapter 6: **CONCLUSION** **62**
BIBLIOGRAPHY **64**
ACKNOWLEDGMENTS **69**

Abstract

Grasping is a fundamental human action involved in our daily interactions with objects. Despite its apparent simplicity, grasping is a complex cognitive and motor process that encompasses various factors. Our cognitive system rapidly assesses the properties of the target object and the intended goal. This assessment will then lead to precise motor instructions that will guide our hand in the execution of the optimal grasp. This evaluation allows for the employment of different techniques based on the characteristics of the target and of the action required. For instance, precision grip is typically employed for smaller and more delicate objects, while multi-digit grips are used when greater force is needed or when interacting with larger targets. Additionally, the advent of Virtual and Augmented Reality (VR/AR) technologies has paved the way for investigating how individuals adapt their grasping behaviour in virtual and mixed environments. These immersive technologies offer unique opportunities to explore the interactions between human cognition, perception, and motor control in virtual settings.

This study presents an experiment aimed to examinate grasping behaviour of participants in unconstrained and precision grip conditions. The experiment involved interactions with objects of various shapes and material composition, with the movement of participants' hands and objects tracked using reflective markers.

The findings reveal that precision grip is not the natural grip employed by humans in unconstrained conditions; instead, a multi-digit grip is preferred. Moreover, the study highlights the influence of material composition in grasping behaviour. Additionally, a novel method for co-registering real and virtual objects using motion-tracking data is introduced, offering potential applications in the investigation of grasping behaviour in virtual and mixed reality environments.

These findings contribute to a deeper understanding of human grasping behaviour and pave the way for further research and advancement in various fields, such as rehabilitation, robotics, and Artificial Intelligence (AI).

Chapter 1: **INTRODUCTION**

Grasping is a fundamental action performed by humans in their daily lives to interact with the world around them. Despite its seemingly effortless nature, it is a complex process that allows us to instinctively select the optimal hand configuration to effectively engage with objects and achieve our intended interactions.

This intricate process of grasp selection involves the integration of various factors encompassing both our cognitive abilities and biomechanical constraints, combined with the properties of the objects themselves.

After an evaluation of such properties, humans have the ability to quickly and accurately identify the optimal grasp configuration required to perform a specific task. This detection process takes into account not only the properties of the objects themselves, but also the particular nature of the interaction required.

The primary objective of this study is to examine the default grip employed by humans when grasping objects and determine if the precision grip is the dominant technique or if alternative gripping methods are preferred. Additionally, this research aims to expand upon previous investigations by exploring the transition from precision grip to unconstrained conditions. Furthermore, a key aspect of this study involves the development of a novel method for co-registering real and virtual objects, which will serve as a foundation for future exploration of grasping behaviour in virtual and mixed reality environments. Through these investigations, this study aims to contribute to our understanding of human grasping behaviour and pave the way for further advancements in the field.

In the initial section of the thesis, I will provide a comprehensive overview of the fundamental aspects of grasping that will be investigated in this study. This overview will be presented in the form of a literature review, which will include a selection of relevant studies related to the topic, as well as definitions and concepts that will be utilized throughout the study.

Following the literature review, the aim of the study will be articulated, along with the specific research questions that will be addressed. Such research questions will serve as the guiding framework for the subsequent investigations and analysis conducted in the study.

1.1. Literature review

In this section I will provide a summary of different studies involving grasping and the different aspects involved in such an apparently simple but at the same time complex task.

1.1.1. Precision vs multi-digit grip

In terms of grasp configuration, a key distinction can be made between precision grip and multi-digit grips.

When humans wish to dexterously grasp a small object, they usually employ a precision grip (1). Such technique involves using the thumb and one or two fingers to hold and manipulate objects with fine control. In this thesis, I will specifically investigate the use of precision grip defined as the involvement of just the thumb and index finger. The objects for which such technique is commonly employed are usually small objects that require careful handling and precise control of forces while the action is performed. Humans tend to employ a precision grip when the required distance of thumb and index is smaller than 2.5 cm (2). Such action relies on rotation at the carpometacarpal joints of the thumb and index. It engages various small muscle of the hand, combined with the *flexors digitorum profundus* and *superficialis*, and *pollicis longus* muscle. These muscles (35) work in coordination to achieve the necessary grip strength and control for performing tasks with precision.

Within the precision grip technique, different types of gripping techniques can be distinguished based on the specific hand configuration and contact points with the objects:

- *Terminal opposition*: This technique provides the highest level of accuracy in all precision grips. It involves the use of the tips of the thumb and index pads (and occasionally even the edges of the nails) for the interaction with objects.

- *Subterminal opposition*: This is the most commonly used type of precision grip. The contact with the object in this case is executed involving the palmar surface of the thumb and index finger.

- *Subtermino-lateral opposition*: This technique allows for increased strength. In this instance, the pad of the thumb presses against the side of any of the phalanges of the index finger.

- *Adduction between two fingers.* In this particular precision grip, the thumb does not play any role. The adduction occurs is usually between two other fingers, typically index and middle fingers. The absence of thumb involvement leads to weaker and less precise force exertion.

In this study, the focus will be on precision grip as a grasping technique involving the use of just two fingers, namely the thumb and index finger. The interaction with objects will occur exclusively using the tips of the finger pads, aligning with the *terminal opposition* grip configuration.

For many years and still to these days, research on grasping focuses mainly on precision grip ((4) - (8), (20) - (25)), given its relatively simpler nature and common use for parallel contact surfaces. However, in the early 2000s and continuing to the present, there has been an increasing interest in studying the complexities of multi-digit grasping ((9) - (17)). Researcher have recognized the importance of investigating the various configurations and dynamics employed in grasping involving multiple fingers. Such studies aim to understand the coordination, force distribution and tactile feedback among different digits when interacting with objects. This expanded focus has provided valuable insights into the versatility and adaptability of human hand function and has expanded on our understanding of the complexities involved in object manipulation.

Multi-digit grasps are employed when dealing with more complex items or tasks that prioritize force and comfort over dexterity. This grip involves using multiple fingers to grasp and manipulate objects, allowing for a more secure and stable hold. Unlike the precision grip, which emphasizes fine motor control and precise manipulation, the multi-digit grip provides greater strength and versatility in handling objects that require a firmer grasp or exertion of force.

When it comes to multi-digit grasps, many different taxonomies can be defined (11). Just like with the precision grip, which, as illustrated earlier has specific types such as terminal opposition, subterminal opposition, subtermino-lateral opposition, and adduction between two fingers, the multi-digit grip can vary in the combination of finger used, the placement of fingers on the object, and the level of force applied. This results in more adaptability and versatility in grasping objects of different sizes, shapes, and material composition.

In multi-digit grips, regardless of the specific categorizations, one aspect remains consistent: the involvement of the thumb along with a combination of the other four fingers.

This collective group of fingers is sometimes referred to as the virtual finger (VF). Such concept ((9), (15)) essentially combines the mechanical contribution of multiple fingers into a single unified entity. The notion of the virtual finger has been used in the literature ((9), (16), (17)) to study the coordination and interactions in behaviour of the thumb and other digits during multi-digit grasping tasks. A more precise and accurate depiction of the interaction is obviously given if considering the individual fingers (IF), by this criterion (9), all the fingers are evaluated as a single entity and therefore the behaviour and interactions between single digits can be better addressed.

Therefore, considering the individual fingers (IF) allows for a more detailed and accurate analysis of the interactions. By evaluating each digit as a single entity, it is possible to gain a more complete understanding of the specific contributions and interactions between the individual fingers while performing grasping tasks. The study of individual fingers allows for the discovery of which function is attributed to each specific digit. Notably, such insights may not be captured by considering the fingers as a collective entity, such as the virtual finger (VF). Therefore, analysing the behaviour and interactions of individual digits offers a more comprehensive and accurate depiction of the intricacies of multi-digit grasping.

In the following study, a multi-digit grip is defined as a grasping technique that involves the thumb and at least one other finger, with the interaction between the fingers and the object occurring exclusively at the tips of the finger pads. This clarification allows for the inclusion of precision grip among the multi-digit grips.

Figure 1 illustrates a depiction of the two grasping techniques.

Using such definitions enables a fair comparison between precision grip and multi-digit, as both involve the use of specific finger combinations and focus on the interaction at the distal ends of fingers.

To conduct this comparison, the study will investigate human grasping behaviour in both unconstrained and strictly precision grip conditions. By maintaining consistency in the interaction method while varying the number of fingers that can be employed, a precise comparison in performance, characteristics, and features in play for precision grip and multi-digit can be conducted. Such approach will offer valuable insights into the differences and advantages of these two grasping techniques and will provide a better understanding of human hand function and dexterity.

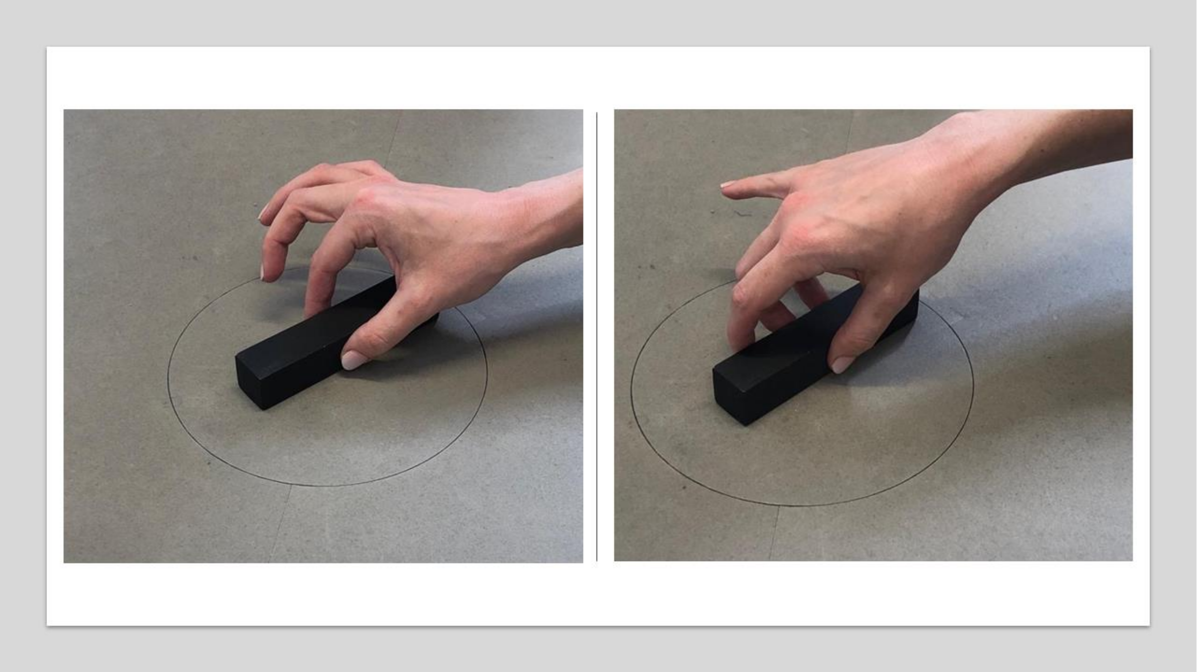

Figure 1. Comparison Between precision and multi-digit grip

1.1.2. *Influence of objects features.*

Having defined the distinction between the techniques I will investigate in this thesis, it is necessary to evaluate the role that the features of an object play in the process involved in the identification of the ideal grasping technique.

Intrinsic characteristics of the objects, such as their shape, surface friction, mass, mass distribution ((6), (18), (21)), and material appearance ((20), (21)), play a pivotal role in guiding our interaction with the objects. Our brain rapidly assesses the relevance of these distinctive features and determines the optimal contact points on the objects for a successful grasp.

External features of the objects such as their position (22) and orientation (20) exert a considerable influence on the nature of the interaction. The position of an object in space can affect the accessibility and visibility (7). For instance, if an object is placed far away or in an awkward position, it may require us to adjust our hand posture or approach angle to successfully grasp it. Similarly, the orientation of an objects affects the stability of the grip. An object that is oriented in a challenging or unstable manner may require us to employ specific grasping strategies or modify our hand posture to achieve a secure and functional grip.

Both internal and external factors of the objects play a role in grasping, but they do not have the same extent of influence.

A specific study that is the foundation of this thesis, was conducted by Klein et al., 2020 (6).

In the study the researchers created a rich dataset in which they could address how different aspects of an object, such as its shape, mass, mass distribution, and orientation influence grasp selection. Specifically, the relative importance and interaction of such features was assessed.

Particularly related to this thesis is the second experiment they conducted, in which they varied the mass and mass distribution of objects to test the relative role of 3D shape and mass properties. In particular, if subjects consider torque as a fundamental characteristic in the identification of ideal precision grip grasps, same shape objects distinguished by different mass distributions should result in systematically different grasps.

In the first experiment they presented participants with four different shaped objects made of 10 wooden cubes, and each of them weighted in total 97 g. Each of the objects would be presented at one of two possible orientations in respect to the participant. Participants were asked to pick up the object strictly performing a precision grip and place it at the goal location. Participants fingertips movements were tracked using an Optotrack 3020 infrared tracking system.

The results illustrate how, when presented with mono-material objects, participants behaved rather consistently. For each condition, different grasps have similar sizes and orientations, and cover the same portions of the objects. When interacting with lightweight objects, humans don’t really care about torque. Based on the shape of the objects, participants mainly selected only one (70%), or two modes (27%) ad only rarely grasped objects in three different locations.

In the second experiment, the emphasis shifted on the influence of mass and mass distribution. To investigate these factors, objects with identical shapes to those one used in the first experiment were employed, but with increased mass and asymmetric mass distribution. This was achieved by replacing five of the ten wooden cubes with brass cubes and arranging them in different configurations. Three different versions of the objects were obtained: two bipartite objects, with brass on one or the other side and wood on the other half, and one object with alternating brass and wood cubes.

The findings from the second experiment indicate that the material composition of the object affected participants' grasping behaviour, resulting in a shift in their grasp towards the center of mass (CoM) of the objects, although not consistently. Specifically, it is important to notice that, when the CoM was shifted closer to the hand's starting location, there was no significant adjustment observed in participants' grasp compared to experiment 1. However, when the CoM was shifted farther from the hand's starting point, a greater adjustment in participants' grasp was observed. These differences in behaviour can be interpreted as participants' explicitly estimating the object's CoM on the basis of visual cues.

An example of the results obtained for this experiment is depicted in *Figure 2*.

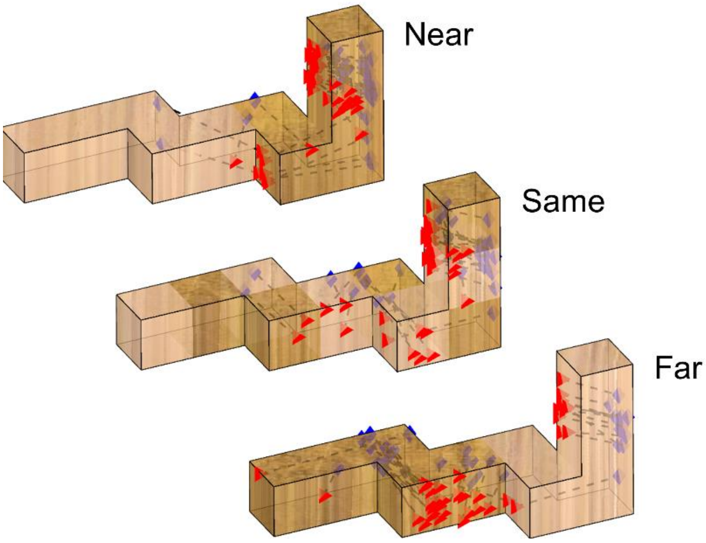

Figure 2. recorded grasp for a particular object in experiment 2 of the study by Kein et al. (6).

The combined findings from the two experiments indicate that participants consider multiple factors when selecting grasp's locations. Among these factors, primary role is played by shape, weight, orientation, and mass distribution of the objects, as well as properties of their own body. By combining these various aspects, participants are able to detect the optimal contact points for grasping the objects. This highlights the complexity and multi-dimensionality of the grasping process, which integrates both object-related and body-related factors in order to generate an efficient and effective interaction with the environment.

Furthermore, on the basis of observations illustrate in a study by Kleinholdermann et al. (21), they developed a computational model able to identify, given the physical stimuli as input, the optimal grasp locations on the surface of such object. Such model was constructed on the basis of different functions related to both objects feature (size, shape) and factors related to the human hand, such as its degrees of freedom.

They identified different constraints involved in two digits grasping, the strongest of which was the *force closure,* meaning the alignment of surface normals at contact locations. Other constraints implemented included:

- *Natural grasp axis,* indicating that humans tend to prefer a specific hand orientation, known as the natural grasp axis (NGA, (23)- (25)).
- *Grasp aperture,* as illustrated earlier, humans tend to employ precision grip for relatively small objects, for which the required distance at contact is smaller than 2.5cm (2).
- *Minimum torque,* another factor in the selection of the ideal grasp is the attempt in reducing the rotation of the object when manipulated.
- *Object visibility,* it is important to consider that, when interacting with an object, the hand could interfere with the visibility of the object.

These observations were employed in a further study by Maiello et al. (7) in which it was explored whether the mere visual observation of the external feature of an object is adequate for assessing the quality of grasps. The main focus was to investigate the cognitive processes involved in selecting the most suitable precision grip grasp configuration out of the many possibilities that would lead result in a stable grip.

Based on the criteria of the model developed in the study by Klein et al. (6), the researchers conducted different experiments in which they investigated if humans could evaluate all these constraints using only their sight or if a haptic interaction is necessary.

The results demonstrated that while visual examination alone was generally sufficient for the evaluation of optimal grasp, actual physical execution of the grasps led to significant improvements in performance. Notably, the subjects who initially performed poorly during the visual examination session exhibited the most notable improvements from physically executing the grasps.

These findings suggest that, even though using visual assessment humans can obtain valuable information in the evaluation of grasping, it is through haptic feedback and proprioceptive info obtained while actively interacting with the objects that they gain a deeper understanding of the grasp quality. The sensory information generated by the fingers and hand movements plays a fundamental role in the adjustment necessary to gain optimal stability.

The article's results highlight the necessity of a combination of visual information and haptic feedback given by the physical interaction to amplify grasp performance. This emphasizes the importance of sensorimotor integration involved in the grasping and underlines the primary role of haptic perception in refining grasp control and stability.

Following on the findings from these previous researches, the same group conducted a subsequent study (8), in which they examined the influence of an object's external appearance and its orientation on our way of interacting with it. The researchers observed that when participants were presented with a choice between unusual grasp configurations and grasp stability, the latter was found to be the main determining factor. The experiment involved asking participants to perform simple grasping tasks involving different objects. The objects were made of the same material. However, they were differentiated based on variations in their surface coating and orientation. This allowed the researched to isolate the influence of these specific features on participants' grasp behaviour. By manipulating the surface coating and orientation of the objects while keeping their material constant the study aimed to investigate the impact of these visual cues on the participants' choices in grasp configuration.

The findings of the study indicate that participants prioritize grasp stability over grasp configuration. They observed that participants opted for a grasp in the higher friction surfaces more frequently compared to the lower friction ones.

Such outcome highlights the fact that humans tend to select grasp endpoints that promote stable grasps, even if that leads to the execution of unusual grasp configurations. The study emphasizes the importance of grasp stability as a significant factor in human grasping behaviour, even in cases where it deviates from the preferred natural grasp configuration.

The studies discussed so far have primarily focused on the aspects regarding the interaction with objects when employing precision grip. As indicated at the beginning of the chapter, grasping behaviour can be distinguished into two main categories: precision and multi-digit grasping. Additionally, in the previous discussions, the concept of contact points was emphasized. However, in actuality, grasping involves contact areas rather than precise points.

A recent study by Hartmann et al. (12) addresses both these limits. In this study, the researchers use state of the art tracking software to investigate interactions between hand and objects while grasping. The method utilizes specialized hardware and software developed by Qualisys, a motion capture company. The experimental set up includes six video cameras (Qualisys Miqus Video), which record the scene. Additionally, the movement of participants' hands and of objects is tracked using eight tracking cameras (Qualysys Miqus M5). These tracking cameras are able to accurately monitor the motion of reflective markers within the tracking volume at a frame rate of 180 frames per second. Moreover, they allow for a sub-millimetre 3D spatial resolution, enabling precise tracking and analysis of hand and object movements during the experiment.

For this study, custom objects were created using a virtual 3D object model and subsequently 3D printed. Reflective markers are carefully placed on both the objects and the participant's hands following a precise protocol. This allows for accurate identification of individual hands among different participants based on the distance within correspondent markers for each subject. The employment of this approach allows for the generation of a detailed mesh representation of both the participants' hands and the objects, enabling further analysis and examination of their interactions.

Once the 3D mesh models of a participant's hand and a grasped object are obtained, it becomes possible to estimate the regions of contact between the hand and the object. This is achieved by calculating the intersection between the meshes of the hand and the object, which identifies the specific areas where contact occurs.

Therefore, this method enables the investigation of contact regions rather than singular points in multi-digit grasping. What sets it apart is the comprehensive protocol used for tracking both the hands and the objects. In the studies presented so far, the movement of the participant's hand was either not tracked ((7)- (8)) or just the thumb and index were tracked (6). Additionally, the objects involved were never tracked. By implementing this protocol, a fair comparison between precision and multi-digit grasping could be conducted. Furthermore, the Qualisys system provides highly accurate tracking of marker movements, allowing for precise identification of the hand used for interaction and the rigid body (object) being interacted with.

The literature review presented here provides several notable observations. Firstly, on the basis of the definitions provided here a clear distinction can be made for precision and multi-digit grasping demonstrating clear differences in technique and purpose. Each technique is suited for specific tasks and accompanied by its own advantages and limitations.

Additionally, the review highlights the significant role of physical properties of objects and their impact on the interaction with them.

The study presented in this thesis aims to integrate these various aspects and explore how they are interrelated within the intricate cognitive processes involved in visually guided grasping.

1.1.3. Grasping in Virtual and Augmented Reality

Virtual Reality (VR) and Augmented Reality (AR) technologies are becoming increasingly prevalent in various fields, including recreation, industry, medicine and rehabilitation. Despite grasping being a fundamental human behaviour, there is limited understanding of how individuals adapt their grasping behaviour ((26)- (29)) in VR/AR environments. In conventional VR, objects are intangible, preventing users from physically touching them. However, certain physical behaviours, such as objects falling under simulated gravity, can be replicated. This raises the question of how humans adapt their behaviour when they reach and manipulate objects without the ability to touch them or perceive their physical properties such as surface compliance or weight. In AR environments, both physical and virtual objects coexist, enabling alterations in the visual appearance of physical objects. Additionally, the change in behaviour of humans when they can touch some objects but not others, and when the appearance of objects deviates from everyday experience, is an important consideration.

Different studies have addressed the interaction between humans and objects in a virtual and mixed environment ((26) - (29), (33)), replicating well known effects, such as the size-weight illusion (33) and discovering new illusions, such as the virtual weight illusion (28).

An interesting study in such regards, has been conducted by Chessa et al. (26), which aimed to replicate the experiment conducted by Klein et al. (6) in a VR environment. The goal was to investigate whether the findings observed in Klein et al.'s study would hold true in the context of VR. By recreating the experimental setup and tasks within the VR environment, Chessa et al. (26) sought to examine if participants would exhibit similar grasping behaviours and if the factors influencing grasping identified in the original study would still hole in the VR setting.

The results of the study indicate that participants in the virtual environment struggled to accurately grasp objects by placing their fingertips on opposing object surfaces. Instead, they tended to interact with the objects in physically impossible grasp configurations or even penetrate them. This observation suggests that the absence of a naturalistic grasping technique in the virtual environment may contribute to these inaccuracies. However, it is noteworthy that the overall selection of virtual objects by participants broadly agreed with the grasping patterns observed in the study by Klein et al. on real objects.

These findings highlight the challenges and differences in grasping behaviour between real and virtual environments, emphasizing the need for further research to improve the realism and fidelity of virtual object interactions in order to enhance user experiences and performance in VR.

1.2. Objectives

This section introduces the objectives of the study, including the research questions that were explored in this study, along with the anticipated outcomes.

1.2.1. Is unconstrained grasping precision grip?

In the literature review I presented a definition for multi-digit and one for precision grip. Based on these definitions, it is reasonable to speculate that precision grip could be considered as a subset of multi-digit grip. Therefore, the first part of this study will revolve around the observation of whether, when given the option to use as many digits as they wish, participants will predominantly employ a precision grip.

This part of the analysis focused on examining participants’ behaviour during the unconstrained session. The main focus was to determine the preferred number of digits participants would employ when unconstrained and whether they would predominantly opt for a precision grip in such situations. It was investigated whether the precision grip is the default grasping technique naturally adopted by humans when no specific constraints are imposed.

If precision grip is the natural grip, participants would employ such technique when left unconstrained, if multi digit grip is instead their preferred technique, when given no constraint participants would use more than just two fingers.

1.2.2. Do material composition and grip technique influence grasping?

In the literature review, I discussed in detail different studies ((6) - (8), (12)) that examined visually guided grasping objects with various shapes and material composition. Among these studies, three specifically focused on precision grip grasping. Notably, the second experiment conducted by Klein et al. (6), investigated how the material composition influences the contact points between subjects and objects when performing precision grip grasping. Building upon these findings, this study aims to extend the investigations to unconstrained grasping. To achieve this, I utilized a subset of objects from the aforementioned study (which will be described in more details in the methods section) and have participants perform visually guided grasps in two distinct sessions. The first condition involved grasping without any constraints, while the second condition specifically required precision grip. By comparing the outcomes of these two conditions, further insights in the processes involved in grasping behaviour can be provided. Firstly, I examined whether the findings from (6) regarding the influence of material composition in precision grip grasping, remained consistent when participants are not given explicit instructions in regarding the grasping technique to use. This investigation aimed to determine if the material effects observed in precision grip grasping are generalizable across different grasping techniques.

Secondly, I explored whether the interaction with objects, and consequently the contact points established, were influenced by the specific gripping technique employed. By comparing the grasping outcomes between the unconstrained condition and the precision grip condition, I was able to assess if the chosen grasping technique has an impact on the selection and placement of contact points during visually guided grasping.

Based on previous findings, it seems likely that participants will demonstrate a similar trend of adjusting their grasp to interact with objects closer to their CoM in the current study as well. This would suggest a consistent behaviour in response to the influence of material composition on grasping.

Furthermore, I anticipate a distinct change in the interaction pattern when participants perform precision grip and unconstrained grasping tasks. As per the here presented definition, precision grip involves the use of thumb and index finger, focusing on precise manipulation and control. On the other hand, multi-digit grasping involves the use of the thumb and multiple fingers, emphasizing comfort and force. It’s expected that if these different techniques affect the interaction with the objects than this will result in variations in the choice and placement of contact points during grasping tasks.

1.2.3. Is material composition the primary determinant factor in visually guided grasping?

In the literature review, I have illustrated how grasping behaviour is influenced by several factors beyond the material properties of the objects. These additional factors play a significant role in shaping the way humans perceive, plan, and execute their grasping actions. Some of the key factors that have been investigated include shape, surface appearance, visibility, and reach distance, among others.

The aim of these section of the study was to investigate the extent to which material composition influences visually guided grasping, and if it represents the primary aspect considered.

Specifically, I focused on comparing the distance between contact points and CoM of the specified objects, by contrasting the results for objects with inverted material composition. If the CoM is the primary factor influencing grasping behaviour, it is expected that the distances between contact points and the CoM will be similar for objects with inverted material composition. This would suggest that participants adjust their grasp to align with the CoM, regardless of proximity or comfort. Conversely, if the CoM is a contributing factor, but not the main one, different distance values from the contact points will be observed.

By analysing these distance measurements, I aim to determine the relative importance of material composition and CoM involved in visually guided grasping. This will provide insights into the underlying mechanisms adopted during participants’ grasp behaviour and identify key factors influencing their interaction with objects.

The expectation is that the distances will vary for objects with inverted material composition, as a consequence of the fact that the grasp location might change in order to provide more stability in the interaction with the object and avoid high torque. While it has been established that material composition has an influence on grasping, this study aims to investigate the fact that it could not be the main factor, but rather other aspects, such as for instance proximity have a more key role. Based on this expectation it is anticipated that participants may prioritize vicinity to the object's CoM to some extent, but other factors may play a larger role in guiding their grasp behaviour. These additional factors may lead to variations in the distance between the contact points and the CoM.

Furthermore, I aim to investigate if the aforementioned influence of material composition on grasping remains consistent when performing precision or unconstrained grasps. To explore this, I conducted a similar investigation, but differentiate between precision and unconstrained grasps.

If the distance from the CoM is not substantially affected by the grasping technique employed, I would expect to observe similar values. This would suggest that the influence of material composition on the selection of contact points remains consistent regardless of the specific grasping technique used.

Therefore, it's anticipated that the result will demonstrate consistency between precision and unconstrained grasping techniques, leading to similar values in terms of the distance from the CoM. This outcome would support the notion that the influence of material composition is coherent between grasping techniques.

1.2.4. Development of a co-registration method for the alignment of real and virtual objects.

In the last section of the literature review, the focus was on the emerging topic of grasping in virtual environments. The main question addressed in this context is whether the virtual appearance of an object influences how humans interact with it. To investigate this question, it is essential to develop a method that enables the co-registration of real and virtual objects within a motion capture environment.

Co-registering real and virtual objects involves aligning their positions and orientations in physical and virtual spaces. This allows for a seamless integration of virtual objects into the motion capture environment, enabling participants to interact with them as if they were real. Such a method would typically involve the use of motion capture technology to track the movements of participants and objects, and advanced algorithms to merge the real and virtual data.

By co-registering real and virtual objects, researchers can study how the virtual appearance of objects influences grasping behaviour. They can manipulate the visual properties of virtual objects, such as their shape, size, colour, or texture, and observe how participants adapt their grasping strategies in response. This approach provides valuable insights into the role of visual cues in grasping behaviour and helps improve the realism and effectiveness of virtual object interactions.

Overall, the development of a co-registration method for real and virtual objects within a motion capture environment is a crucial step in investigating the impact of virtual object appearance on grasping behaviour in virtual environments.

In the last section of the thesis, a method is presented for co-registering real and virtual versions of the same objects using tracking data recorded from the motion tracking software Qualisys. This method involves tracking the position of a user and real objects using markers. With this tracking data, a virtual environment is rendered from the user's viewpoint, containing realistic replicas of the real objects.

To validate the accuracy of this co-registration system, a novel validation procedure is proposed. The virtual environment is rendered from the same viewpoints as the motion tracking cameras used to record the tracking data. By comparing the rendered virtual scene with the real scene captured by the cameras, the alignment between the real and virtual scenes can be measured.

This validation procedure allows for the assessment of the accuracy and reliability of the co-registration method. By quantifying the alignment between the real and virtual scenes, any discrepancies or misalignments can be identified and addressed. This ensures that the virtual environment accurately reflects the real environment.

Overall, the development of this co-registration method and the validation procedure contribute to the integration of real and virtual objects in a motion capture environment. It enables researchers to study grasping behaviour in virtual environments with a high level of realism and fidelity.

1.3. Thesis motivation

This study aims to provide valuable insights into the grasping process and the interactions between humans and objects during grasping tasks.

While the study by Klein et al. serves as the basis for this thesis, aside for the main extension being the evaluation of unconstrained grasping, there are other significant differences in the setup and methodology employed.

In the original study by Klein et al. (6), the movement of participants fingers was tracked using an optotrack system. However, in this study, the previously introduced method developed by Hartmann et al. (12), will be employed. The movement of participants hand's will be tracked using the Qualisys system, allowing for a more accurate tracking and analysis of hand movements during grasping.

Furthermore, an extension of Klein's study will involve tracking the objects employed in the experiment. This additional tracking will provide valuable information about the object's position, orientation, and movement during grasping, allowing for a more comprehensive understanding of the grasping process.

By utilizing a different tracking system and incorporating object tracking, this study aims to expand on the findings of Klein et al. (6) and provide further insights into the complex nature of grasping behaviour.

Additionally, the development of a method for the co-registration of real and virtual objects within a motion capture environment will facilitate further explorations of visually-guided grasp movements in Virtual and Augmented Reality. This method will serve as a foundation for my upcoming PhD research, which aims to investigate how visually-guided grasp movements are influenced in VR/AR compared to real-world scenarios.

Chapter 2: **METHODS AND MATERIALS**

The following section will provide an overview of the fundamental aspects related to the conduction and analysis of the study.

2.1. Participants

A total of 20 participants were recruited for the study, all of whom met the following criteria. Participants were either students or stuff members from Justus Liebig University Giessen. They participated in the study either for course credit or financial compensation at a rate of 8 Euro/h. The group consisted of 15 females and 5 males with a mean age of 26,7 years (range: 20-39). Participants had normal to corrected vision and were right-handed. The study procedures were approved by local ethics committee of Justus Liebig University Giessen. The study adhered to the principles outlined in the sixth revision of the declaration of Helsinki (2008).

2.2. Apparatus

The experiment was implemented using *Python 3.7.0* programming language. Participants were seated at a table and their head was positioned in a chinrest 30 cm in height from the workbench. They were instructed to keep their eyes open only for the during the execution of the movement. The objects used in the experiment were placed at a target location on the workbench, which was marked at a certain distance (30 cm) from the chinrest. The experimenter indicated to the participants the specified starting position of the hand.

Following the procedure described by Hartmann et al. (12), the same method for motion tracking was employed in this study.

For the accurate capture of human grasping behaviour, high-precision 3D tracking hardware and software from Qualisys (Qualisys AB, Sweden), a prominent motion capture company, were employed. The tracking set up consisted of 8 tracking cameras (Qualisys Miqus) and 6 video cameras (Qualisys Miqus Video) arranged on a square frame surrounding the workspace. This arrangement allowed for comprehensive recording of the stimuli and participants' hand movements from different angles. Reflective markers were affixed to the top of each object (four markers for each object) and specific landmarks on the back of participants' hands (26 markers) to track their position throughout the experiment.

Figure 3 shows the experimental set up.

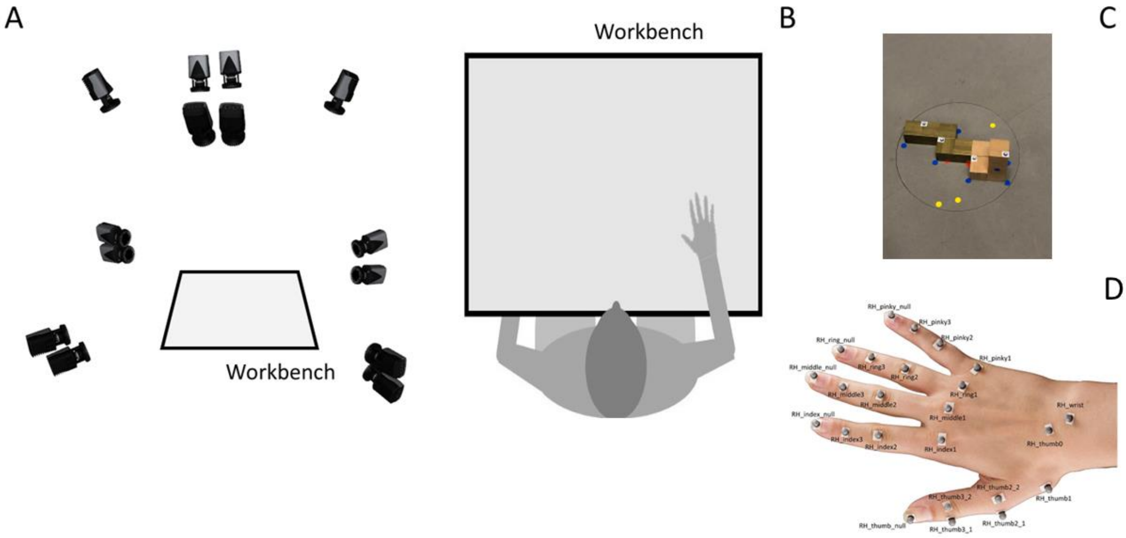

Figure 3. Experimental set up and marker positioning. 3A shows the disposition of the 14 cameras (8 Tracking cameras and 6 Video Cameras). 3B illustrates the initial position of the participant before the start of the experiment. Figure 3C showcase one of the four stimuli highlighting the markers attached in a specific configuration. The different colour of the markers on the workbench (yellow, blue and red) indicates specific position for the V objects, S objects and the training stimuli, respectively. 3D presents the configuration of the markers applied on the back of the participant's hand.

2.3. Stimuli

During the training session of the experiment, a wooden cuboid measuring 6 cm in height and 3 cm in width was utilized as the stimulus. The position and orientation of the stimulus remained consistent across all repetitions.

For both the unconstrained and precision grip session of the experiment, a set of four different objects served as stimuli, distinguished in two possible shape and two possible material compositions. The specific objects were carefully selected as a subset from the larger set of objects employed in the previously presented study by Klein et al. (6). Each object consisted of 5 wooden cubes (2.5 cm^3) and 5 brass cubes (2.5 cm^3), resulting in a substantial weight of 716g. The arrangement of the cubes formed a bipartite structure, with the 5 brass cubes connected to each other on one side and the wooden cubes forming the other side. The sequence of wood and brass cubes was inverted for same shaped objects, resulting in a different CoM location. Each object was presented 5 times in a random order. The objects having the same shapes were presented in the same orientation and same position. The objects were denoted on the basic of their shape (V or S) followed by either B (brass near) or W (brass far) according to the closeness of the brass side to the participants.

For each stimulus a triangulated mesh replica was created using *Blender 3.1.2* (36). The virtual replicas for each stimulus are shown in *Figure 4*.

To ensure accurate tracking and differentiation of the objects, the markers were positioned in specific and distinct configurations for the training stimuli and for each of the four objects. This configuration was designed to enable the Qualisys system to identify and differentiate each object based on the marker arrangement.

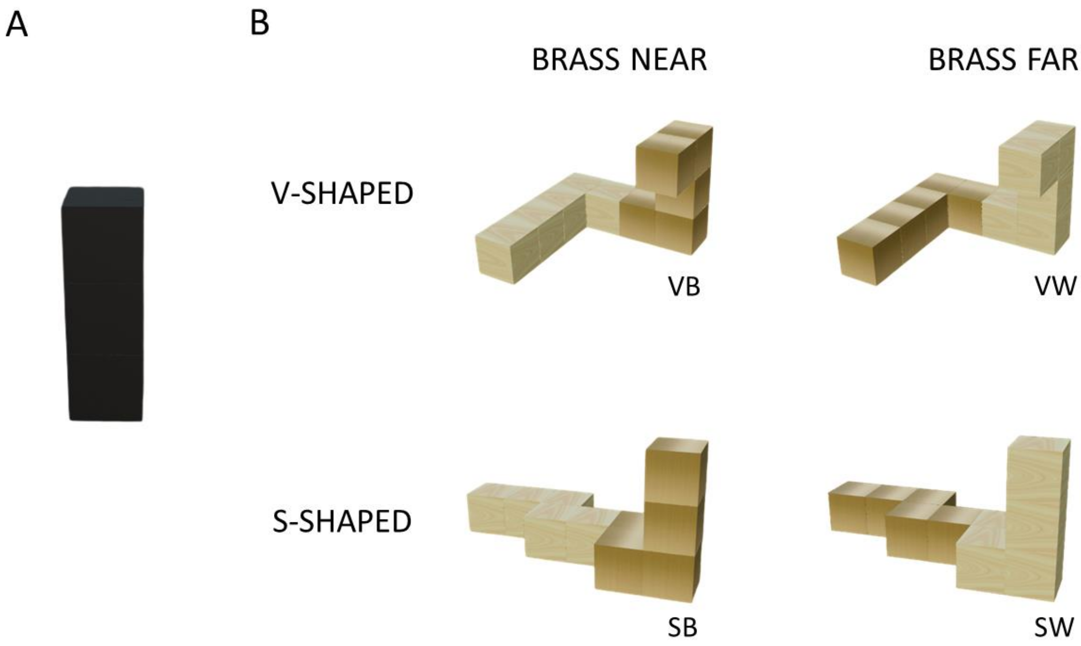

Figure 4. Virtual replicas of the stimuli utilized in the experiment. 4A present the prism employed in the training session. 4B shows the four objects employed in the experiment. These replicas are oriented according to the participant's point of view in the starting position, providing a perspective that mimics the actual viewing angle during the experiment. Each object is labelled below it, indicating its corresponding denomination. The classification is based on the position of the half made of brass and the shape of the object.

2.4. Procedure

The experiment was divided in two separate sessions which were preceded by a single training session. The procedure for both sessions replicated the training session and was largely identical, with the only variation being the grasping technique employed during the interaction with the objects.

2.4.1. Training session

Prior to commencing the experiments, participants underwent a training session to familiarize themselves with the procedure. During the training the participants performed 5 grasping trials for the first stimulus. At the beginning of each trial, participants were instructed to close their eyes while the experimenter placed the training stimulus in a specific position on the workbench using markers as a guide. Position and orientation remained consistent for all five trials. Participants were then asked to place their right hand at a designated starting location adjacent to the workbench and wait for an audio signal with their eyes closed. Simultaneously, the experimenter positioned the object at the starting location. Following the auditory start cue, the participants were instructed to open their eyes, reach out and grasp the object, lift it from the workbench, set it back down, return their hand back to the starting position and close their eyes in preparation for the next trial. If participants still felt uncomfortable with the procedure after completing the five training trials, additional training trials could be conducted.

2.4.2. Unconstrained session

In the first session of the experiment participants performed a total of 20 trials, performing five unconstrained grasping for each of the four stimuli described earlier. The participants' task was broadly the same as in the Training session.

The choice of starting with the unconstrained session as the first session of the experiment was made to ensure that participants' behaviour and grasp techniques were not influenced by any prior interactions or instructions.

The participants were instructed to perform the grasping task however they felt more comfortable, without any restrictions regarding the number of digits used. The order of object presentation was randomized by the experiment's script. Participants were asked to position their right hand at a designed starting location on the workbench and await an audio signal with their eyes closed. The experimenter initiated the script, which indicated the specific object to present for each trial and placed it on the workbench in a predetermined position and orientation. The position and orientation were identified using coloured tape markers glued to the workbench in a specific configuration, which was consistent for objects with the same shape. Upon hearing the start cue, participants opened their eyes, reached out to grasp the object, using their preferred number of fingers, lifted it from the workbench, placed it back down, returned their hand back to the starting position and closed their eyes to wait for the next auditory cue. Participants were asked to place the object back down in roughly the same location, but no specific instruction were given in that regard. This session consisted of four conditions corresponding to the four different objects (two shapes in two material configurations). Each participant repeated each condition five times, resulting in a total of twenty trials per participant. Prior to the experiment participants had no familiarity with the stimuli.

2.4.3. Precision grip session

To ensure a fair comparison, the protocol for the second session of the experiment closely replicated the first, with one modification: participants were instructed to perform a precision grip, utilizing only their thumb and index fingers, to grasp the object. The objects were presented in a randomized order determined by the experiment’s script, just like in the first session. For each trial, the experimenter placed the randomly selected object in a specific position and orientation, which were consistent with the first session and varied based on the two different possible shapes of the objects. Participants were instructed to keep their eyes closed until they heard a sound indicating the start of the trial. Once the cue was heard, they would open their eyes, reach out, and perform a precision grip to grasp the object. They would then lift it from the workbench, place it back down, and return their hand to the starting position.

Chapter 3: **ANALYSIS**

The recorded data from the experiment was analysed using *MATLAB R2021B* software. Data were analysed using a 2 (brass far vs brass near) × 2 (precision vs unconstrained) within-subject analysis of variance (ANOVA).

Prior commencing the analysis, the recorded data from the *Qualisys* software was pre-processed. Each of the four objects used in the experiment was defined as a distinct rigid body, identifiable by its unique marker configuration. Additionally, for each participant a specific AIM (Automatic Identification of Markers) model was created. This model was based on the relative positions of the markers on the participant's hand, as depicted in the previously presented arrangement. The AIM model provided labelled markers on the hand and their corresponding coordinates for each frame of the recorded data. This preprocessing step ensured accurate tracking and facilitated the following analysis.

The aim of the starting part of the analysis was the detection of the first frame in which the contact between the participant and object took place. Subsequently, the analysis involved detecting and documenting the specific contact points involved in the interaction. These observations provided a comprehensive foundation for analysing and understanding the various aspects associated with the participant-object interaction.

To evaluate the contact points of the fingers on the object, a 3D triangulated mesh of the objects was recreated in the 3D computer graphics software *Blender*, ensuring that the replicas were perfectly scaled to their real counterparts. The 3D mesh, representing the objects was then exported to MATLAB for further analysis. This allowed for precise examination of the contact points between the participant's fingers and the object during grasping.

3.1. Roto-translating the objects to their correct position in the *MATLAB* environment.

The initial and fundamental step in the analysis process consisted in the roto-translation of the objects to their correspondent starting positions within the *MATLAB* environment. This was achieved by utilizing the recorded tracking data, which provided information on the position of the markers applied to the objects, and therefore their location and orientation. By evaluating the markers positions, the location and orientation of the correspondent objects at the starting point could be detected. The application of the necessary transformations based on this data allowed for the objects to be accurately positioned in their designated starting position for further analysis.

To achieve the desired result, a Python code was developed to calculate a roto-translation matrix. This matrix, when applied to the object, would correctly position and orient it in the *MATLAB* environment for further analysis. By implementing this code, the objects could be accurately aligned with the tracking data, ensuring that the analysis of the contact points and interaction was precise.

During the execution of the code in *Blender*, the user is asked to select the 3D mesh representation of the object and the *.tsv* (tab-separated values) files of its corresponding markers configuration obtained from the data recorded in *Qualisys*. The *.tsv* files contain the 3D coordinate of the markers and the transformation data for the selected markers configuration. Once the *.tsv* file is selected, a replica of the markers in the correct configuration will appear. The markers are then manually positioned accurately onto the object in the correct location. Subsequently, a roto translation matrix is calculated based on the marker positions and exported as a txt file. This matrix contains the necessary transformation information to correctly position and orient the object in the desired location. Having obtained the matrix, the next step is to proceed with the analysis in *MATLAB*.

Once the mesh of the objects is imported into *MATLAB*, the previously calculated roto translation matrix can be applied to the object. With this operation the object will be transformed to the correct position and orientation. This process allows for accurate alignment and synchronization between the virtual object and the recorded data for further analysis.

3.2. Estimation of frame of first contact between thumb, index finger and object during precision grip

To estimate the frame of first contact during the precision grip trials, a method was developed using the tracking data of the markers on the participants' thumb and index finger. This method was inspired by the MSI-method (34) and involved constructing a combined objective function that incorporated six individual objective functions, each evaluating a specific criterion. By combining these individual functions into a single combined objective function, a comprehensive evaluation of the instance of first contact was achieved.

The individual objective functions were the following:

- F_{vel}. This function evaluated the velocity of the hand markers and assigned a higher value when the velocity at a particular frame was low. The underlying assumption was that the hand's velocity must be at a minimum when the contact between the fingers and the object was occurring. This objective function identified the frames in which the hand's movement suggested the initiation of contact. The incorporation of this function allowed the prioritization of frames with low hand velocity as potential instances of contact.

- F_{sag}. This function was based on the sagittal position of the participant's hands relative to the object. This was a binary function that determined whether the contact was likely to be happening based on the distance between the objects and the hands in the sagittal plane. If such distance in a particular frame was greater than a predefined threshold (100 mm) the F_{sag} objective function had a value of zero, indicating the contact was not likely. However, if the distance was below the threshold, the objective function was equal to 1, suggesting the possibility of contact. By incorporating this function in the combined function, frames where the distances between the hands and the object in the sagittal plane exceeded the threshold could be excluded as instances of contact.

- F_{hei}. This was a function was based on the vertical position of the participant's hand markers relative to the workbench. If the height of the hand markers in a particular frame exceeded a predefined threshold (75 mm), the F_{hei} function had a value of zero, indicating that contact was not likely. Conversely, if the height was below the threshold, the objective function was equal to 1, suggesting possible contact. The inclusion of this function allowed for the exclusion of frames in which the hand markers were positioned significantly above the workbench.

- F_{der}: this objective function was devised to evaluate the first derivative of the grip aperture, which is the distance between the thumb and index finger markers on the participant's hand. It aimed to capture the change in grip aperture as the participant prepared to grasp the object. During the preparation phase of grasping, the distance between thumb and index finger should decrease, as the fingers come closer together. This corresponds to a negative value for the first derivative of the grip aperture. Therefore, the F_{der} objective function was a binary function, that was assigned a value of zero if the first derivative of the grip aperture was greater than or equal to zero, indicating an increasing or constant grip aperture. Vice versa, if the first derivative was negative, indicating a decreasing grip aperture, the objective function was set to 1. By incorporating this function frames where the grip aperture was not decreasing were discarded as instances of contact.

- F_{der2}. This function was designed to evaluate the second derivative of the grip aperture, which indicates the rate of change of the first derivative. Its purpose was to capture the deceleration of grip aperture as the participant's fingers approached the object during grasping. During the grasping action, the grip aperture should not only decrease, but also decelerate, indicating a slowing down of the fingers' closing movement. This results in a positive value for the second derivative of the grip aperture. Therefore, the F_{der2} function was a binary function that had a value of zero if the second derivative of the grip aperture was either negative or null, which indicating either a constant or accelerating grip aperture. On the other hand, if the second derivative was positive, indicating a decelerating grip aperture, the objective function was set to 1. Integrating this function in the combined objective function resulted in the elimination of frames where the grip aperture was accelerating.

- F_{time}. This function was then finally implemented to identify the first frame among all the frames that met the previously mentioned criteria for contact. Once all the individual objective functions were evaluated for each frame, the F_{time} function was used to select the earliest frame that satisfied all the criteria. By scanning through the frames that met the criteria and selecting the first one, this function pinpointed the frame at which the contact between the participant's fingers and the object likely first occurred.

3.3. Estimation of first contact between fingers and object for unconstrained grasps.

Given that for the unconstrained grasp technique the thumb and at least one other finger are involved, it was recognized that the method used for the precision grip session, which specifically focused on the thumb and index finger, would not be suitable for the unconstrained session.

In light of this, an alternative approach was sought to accurately identify the frame of contact during the unconstrained grasping trials. This alternative method aimed to account for the involvement of multiple fingers in the grasp and provide a reliable analysis of the interaction between the participant’s hand and the object. By employing this alternative method, the analysis aimed to ensure an accurate and comprehensive assessment of the contact points and their timing in the context of unconstrained grasps.

For the alternative method employed in the unconstrained grasping session, the focus shifted to analyzing the movement of the markers attached to the objects. A script was developed to process the coordinates of the mean position of these markers and calculate the displacement in the direction perpendicular to the workbench. By tracking the vertical displacement of the markers, the script identified instances where the displacement exceeded a certain threshold. This threshold was necessary to account for any noise or small variation in the data. When the vertical displacement surpassed the threshold, it indicated that the object had started moving upward, implying that the participant had initiated lifting it and that the first contact had occurred a few frames prior to this movement. To quantify the difference between the movement of the object and the frame of first contact a comparison was made between the frame calculated in the precision grip session with the MSI method and the results that would be obtained with this method for the successful trials. The first step was to calculate the difference between the contact estimation provided by both methods. This difference represented the number of frames between the contact estimation of the MSI method and the frame in which the object’s displacement in the direction perpendicular to the workbench exceeded the threshold. Next, the average difference across the considered trials was calculated. This average difference indicated the average number of frames by which the contact estimation of the two methods differed. Finally, this average difference was subtracted from the frame at which the object started moving as determined by the alternative method applied to the unconstrained grasping.

By applying this adjustment, the starting frame of the object movement was refined to account for the discrepancy between the two methods. This allowed for a more accurate estimation of the contact point during the unconstrained grasping trials, enhancing the reliability and validity of the analysis.

3.4. Manual evaluation

It is worth noting that, while the here presented methods proved to be largely successful, there were instances where incorrect results were provided. These errors included situations where the method indicated either no contact or contact with only one finger. The inaccuracies accounted for approximately 10-15% of all the trials conducted. In such cases, an alternative approach was employed. This involved either manual evaluation or, in the specific case the of inaccuracies in the MSI method for the precision grip, the switch to the method used for the unconstrained session.

Manual evaluation of the tracking footage required visual inspection of the recorded data to identify the frame at which contact between the participant’s fingers and the object first occurred. This method relied on the expertise of the researcher to carefully analyse the movement patterns and marker position to determine the precise moment of contact.

By incorporating both the developed method and the alternative approach, the analysis aimed to ensure the accurate identification of contact points in majority of trials while accounting for potential errors or discrepancies in specific cases. This approach aimed to provide a comprehensive and fair analysis of the grasping behaviour observed in the experiment.

3.5. Identification of the contact points on the object

Once the frame of first contact is identified, the next step is to determine the location of the contact point onto the object. This is achieved by analysing the tracking data of the participant’s finger at the frame of contact. By retrieving the position of the fingers during said frame, the distance between this position and all the vertices that make up the mesh of the object can be calculated.

For each vertex of the object's mesh, the distance to marker applied at the tip of the fingers is computed. Notably, for the precision grip session the distance is calculated only for the thumb and the index finger, while for the unconstrained the distance calculation is extended to all the fingers. The vertex that yields the minimal distance is considered to be the point where the participant's fingers are in contact with the object. This approach allows for the precise localization of the contact point on the surface of the object.

By utilizing this approach, the analysis can accurately determine the specific vertices of the object that are involved in the contact.

Once the distances between fingers and object at the frame of contact, as well as the presumed contact points have been identified, several aspects can be evaluated.

3.5.1. Estimation of number of fingers in contact with the object for the unconstrained grasps.

While for precision grips the number of fingers involved in the interaction will always be two, the same observation cannot be extended to unconstrained grasps. In the analysis of unconstrained grasps, an important aspect is the detection of which fingers are effectively in contact with the object.

To determine this, a threshold value (25 mm) was set, and the distances between each finger and the closest vertex at the frame of contact are evaluated.

If the distance between a finger and the closest vertex exceeds the specified threshold, it indicates that the finger is not in contact with the object during the grasping action. In such case, that particular finger is eliminated from the list of fingers in contact. By applying this threshold-based criterion, the fingers that are in direct contact with the object can be accurately identified. The results obtained from analysing the specific finger combinations used during unconstrained grasping can provide valuable inside into the participants' grasping strategies and preferences. By determining which fingers are in contact with the object and evaluating the fingers combination, it is possible to assess if participants tend to employ a precision grip or if they utilize alternative grasping strategies when given no constraints.

It is worth noting that there were instances where no fingers were detected and when only a single finger was detected combining for less than 10% of all the total trials. It is important to note that these instances are physically impossible and are attributed to technical issues during the data recording, likely due to obscured markers.

3.5.2. Estimation of center of contact points (“grasp centroid”).

Once identified the effective contact points between the objects and the participants fingers, a further interesting analysis could involve the evaluation of the center of the said contact points, which will be called from now on “grasp centroid”.

This point was determined as the average location of the contact points involved in each grasp. It provides a reference point that indicates the overall contact position and distribution on the object. This information helps assess whether participants tend to concentrate their contact points in specific regions of the object or distribute them evenly.

Measuring the distance between the grasp centroid and the centroid of the objects allows for evaluating alignment and relative positioning of the grasp. The analysis can reveal important details about the influence of object properties on grasping behaviour. Understanding the relationship between the grasp centroid and the centroid of the object can provide insights into how participants optimize their grasping strategy.

3.6. Co-registration of real and virtual objects

In the data analysis phase, a subset of the recorded data was selected for the development of the co-registration method. This subset included data from one subject and one trial for each condition. This allowed for focused testing and refinement of the co-registration process.

Additionally, five objects from a dataset obtained from the YCB dataset (30) were employed for further evaluation of the co-registration method. This dataset provided both real and virtual replicas of different objects, allowing for comprehensive testing and comparison.

This unique configuration ensured that each object could be distinguished and tracked individually, enabling precise co-registration between the real and virtual representations.

By employing this approach, the co-registration method was systematically developed and validated using representative data from both the experimental subset and the YCB dataset. This ensured the robustness and applicability of the method for the co-registration of real and virtual objects in the study of grasping behaviour in virtual environments.

To accurately track each object, a specific marker configuration was used for each object. Then tracking data for a single participant executing simple grasping tasks for each of the new objects employed was recorded.

The co-registration method employed a new *Python* code, which first uploaded the virtual replica of the selected object on *Blender*. Then, the code utilized the marker configuration data to calculate and apply a roto translation matrix that accurately positioned and oriented the virtual objects within the virtual environment.

To ensure alignment with the real-world environment, the code employed the calibration data to create virtual cameras in the same position and orientation as the real cameras used during the motion capture recording. This allowed for the virtual objects to be viewed from the same perspectives as their real counterparts. To visualize the co-registration, the virtual versions of the objects were overlaid onto their real counterparts, creating a mixed reality environment. This overlay provided a visual representation of how the virtual objects aligned with the real objects in the recorded data.

It is important to note that this co-registration method was implemented using pre-recorded data and was not designed for real-time streaming. However, it served as a valuable tool for the analysis and visualization of the grasping behaviour within the virtual environment based on the recorded data. Specifically, it served as a useful visualization tool that will be employed in this study to illustrate the virtual version of the objects with the projection of the contact points overlaid onto them.

The evaluation of the method's effectiveness was based on the Intersection over Union (IOU) metric. The IOU measures the overlap between specific regions in an image or between two images (31). It provides a value between 0 and 1, where 0 indicates no overlap and 1 indicates complete overlap. To calculate the IOU, a *MATLAB* code was developed. The process begins by creating masks from the images of the virtual replicas of the objects and the video footage. These masks define the regions of interest for each object. The calculation involves determining the Area of Overlap by performing an AND operation between the two masks. This identifies the common area between the masks. Next, the Area of Union is computed by performing an OR operation between the masks, which includes all the pixels encompassed by either mask. Finally, to obtain the Intersection over Union as a percentage, the code divides the Area of Overlap by the Area of Union and multiplies the result by 100.

Chapter 4: **RESULTS**

In the here presented conducted experiment, a total of 20 participants were recruited to perform grasping tasks on four different objects. The experiment was divided into two separate sessions: an unconstrained grasping session and a precision grip session. In the unconstrained grasping session, participants were given no limitations on the number of fingers they could employ during grasping. They were instructed to grasp each object naturally without any specific constraints. In the precision grip session, participants were instructed to strictly employ a precision grip, which, as defined in the introduction, involves using only the thumb and index finger for grasping.

To aid clarity, the objects are labelled based on their material composition in relation to the participant's position. The objects will be categorized as "brass near" (B objects) or "brass far" (W objects) based on the location of the brass half in relation to the participant. This labelling system will help differentiate between the objects and provide a clear distinction based on their spatial relationship to the brass half.

The results will provide insights into the preferred finger usage patterns during unconstrained grasping and the adherence to the precision grip instruction in the precision grip session. They will also shed light on the relevance of different aspects, including object properties and grasping technique, in shaping grasping behaviour. Additionally, an evaluation of the developed co-registration method will be conducted.

The findings will contribute to our understanding of how humans adapt their grasping behaviour in different contexts, such as unconstrained grasping and precision grip tasks.

They will also provide insights into the factors that influence grasping behaviour, such as object properties and grasping technique. Furthermore, the evaluation of the co-registration method will assess its effectiveness in aligning real and virtual objects within a motion capture environment.

Overall, the results and evaluation will contribute to the existing knowledge on grasping behaviour and the use of virtual and augmented reality technologies in studying and simulating real-world interactions.

Error! Reference source not found. displays the virtual replica of the stimuli with the p rojection of the contact points overlaid onto them.

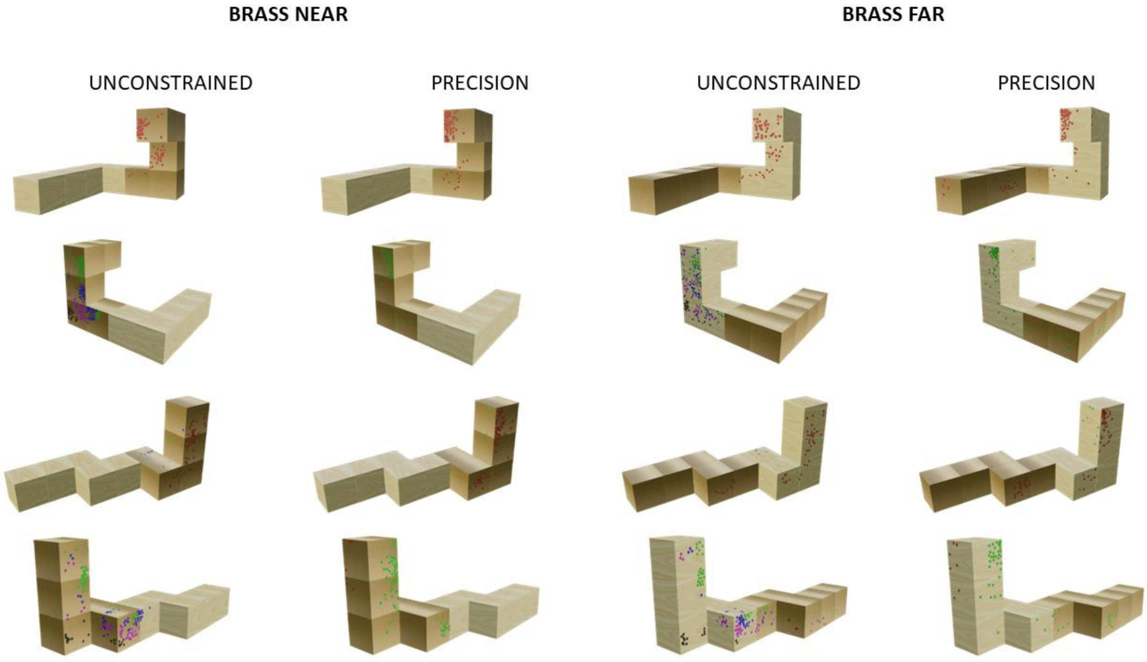

Figure 5. Virtual replicas of all the object with the projection of the contact points. Red dots indicate the contact point for thumb, green for the index, blue for the middle, purple for the ring and black for the pinky finger.

4.1. In unconstrained conditions participants rarely employ just two fingers.

The primary focus of the thesis was to determine whether the precision grip is the default technique adopted by humans when unconstrained as well as the preferred number of fingers participants would naturally employ in such situations. The rationale for beginning with the unconstrained condition was based on the assumption that participants, when given the freedom to grasp objects without constraints or specific instructions, would naturally rely on their inherent tendencies and preferences in interacting with the objects. The aim was to examine whether individuals tend to gravitate towards using a precision grip as their default grasping technique in the absence of any specific constraints.

To address this, the first section of the results will mainly focus on the unconstrained session of the experiment. The analysis of the distance between the fingers and the object during the initial contact provided insights into the fingers predominantly involved in the grasping action for each object. By setting a threshold value, the analysis identified the digits for which the distance fell below this threshold, indicating their active involvement in the grasping process. This method allowed for a quantitative assessment of finger usage during grasping, providing valuable information about the preferred finger configuration. By determining which fingers were primarily engaged in grasping, the study aimed to understand the natural finger usage patterns of participants when no specific constraints were imposed. This analysis contributes to the understanding of how humans adapt their finger usage based on object properties and task requirements.

To validate the method, the same approach was extended to the precision grip session of the experiment. This extension aimed to examine the finger usage patterns when participants were specifically instructed to use a precision grip.

The expectation is that participants, when given the freedom to choose, would frequently employ more than two digits for grasping, suggesting that the precision grip is not the default choice.

Figure 6 depicts the result in the form of a bar graph, presenting a direct comparison of the number of digits employed in unconstrained and precision conditions.

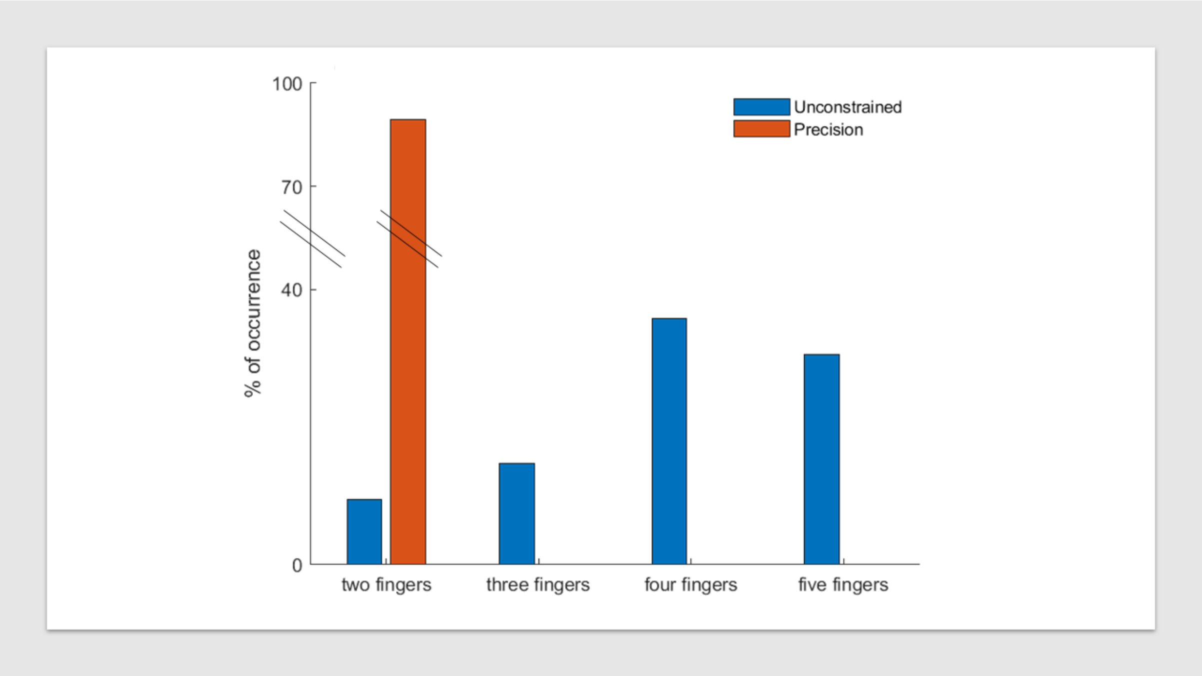

Figure 6. Participants' behaviour evaluated on the basis of finger usage. The different bars show a comparison on frequency of finger usage between unconstrained and precision grip conditions. Each of the bars represent the percentage of instances in which the specific number of fingers was employed. The blue bars depict the unconstrained condition. The orange bar shows the same data for the precision grip.

The results depicted in the bar graph support the hypothesis that humans tend to prefer multi-digit grasping over precision grip (h=1, $p<0.001$).

As predicted, the precision grip results show an almost entirely use of just two fingers, validating the approach employed in the study and indicating that participants followed the instructions.

Out of the total 400 trials in the unconstrained finger usage condition, only 9.5% of the trials involved to use of two fingers. The usage of three fingers was slightly more frequent, occurring in 14.75% of the trials. The majority of the participants opted for either four (35.75%) or five (30.5%) fingers in their grasping strategy. This suggests that when given the freedom to choose, individuals naturally gravitate towards using multiple fingers to grasp objects.

These findings provide valuable insights into the preferred finger usage patterns of individuals during unconstrained grasping tasks. They highlight the importance of considering multi-digit grasping as a common and natural strategy employed by humans, challenging the notion that precision grip is the default choice. The majority of participants in the study chose to employ either four fingers or all fingers in their grasping behaviour. This indicates a natural inclination towards using multiple fingers for grasping objects, rather than relying solely on a precision grip with just two fingers.

4.2. Material composition and Grip Technique have an impact on grasping behaviour.

In the following section of the results, we evaluated which of the conditions imposed play a role in the human's decision making for grasping.

The experiment included three conditions, given by: shape of the objects, material composition of the objects and grasping technique. Though two different shapes were employed in order to generalize the participants behaviour, the distinction in object's shape was not considered in the analysis. The decision was to concentrate the analysis on how material composition and grasping techniques affected participants' interaction with the stimuli. ANOVA analysis revealed a significant main effect of material configuration ($F1,19 = 6.16$, $p=.023$), a significant main effect of grasp configuration ($F1,19 = 6.64$, $p=.019$), and no significant interaction effect ($F1,739 = 0.96$, $p=.33$).

In this section of the results, the focus was on the geometrical centroid of the objects, which coincided with the point of material change for all objects. Subsequently, the distances between said point and the grasp centroid for the participants in the different conditions was calculated.

If material configuration is not a determining factor, grasp positions will be consistent, regardless of the proximity of the brass part of the object to the participant. On the other hand, if material configuration does exert an influence, there will be clear variations in grasp position in relation to the object centroid between the brass near and brass far condition.

Building on previous research ((6), (19) - (22)) it is reasonable to expect that minimizing torque will be one of the goal of participants when grasping the objects. Consequently, in the brass far condition, it is expected that participants will grasp the object on the side farther away from them more often than in the brass near condition. This behaviour aligns with the principle of minimizing torque and provides further support for the influence of material configuration on grasp selection.

Moreover, if grasping technique plays a role in grasp selection, the results will reveal distinct values in the distance between the centroid of the object and the grasp centroid when categorizing them based on the employed technique. This analysis will shed light on the influence of grasping technique on the spatial relationship between the object and the points of contact during grasping.

Overall, these analyses aimed to provide insights into the intricate relationship between material composition, grasping techniques, and the decision-making process in object grasping.

4.2.1. Material composition has an impact on both precision and multi-digit grasping.

Figure 7A presents the mean distances between object centroid and grasp centroid for all the subjects, categorized by the material composition of the objects.

As predicted, the data reveals that distances for the brass near objects are tightly clustered around similar values and on the same side. All recorded values are negative, indicating that participants consistently made contact with the objects on the side closer to them. This outcome confirms the anticipation that when the heavier side coincided with the side closest to the participants, they uniformly grasped the objects at approximately the same location.

In contrast, the analysis reveals distinct behaviour for objects with the heavier side located farther from the participants (brass far). The recorded distances for these objects demonstrate greater variability in terms of magnitude and sign. The plot clearly illustrates that three specific subjects had mean distances with positive values, indicating a general inclination to grasp the object from the side farther from them.

Upon observing the colours of the lines connecting corresponding subjects within-subject behaviour can be evaluated. Aside from the three red lines connecting the previous mentioned participant for which the mean was positive, it is notable that for an additional five subjects, although the mean falls on the side closer to them, the grasp centroid was on the side of object farther from them at least once. This suggests that the material composition had some effect on their behaviour, leading them to alter their behaviour when presented with different material compositions.

Upon examination of *Figure 7B and Figure 7C* , which provide a more detailed view of the effect of material composition in the two sessions, the following patterns can be observed.

In the unconstrained session (7B), the mean distances were positive for four subjects in the brass far objects, indicating a preference for grasping the object from the side farther from them. Additionally, three more subjects exhibited at least one instance of grasping the object from the farther side. In the precision session (7C), the mean distances were positive for four subjects, and one additional subject displayed grasping the object from the side farther from them. It is worth noting that the subjects performing at least one grasp on the father side were not necessarily the same in both sessions.

These findings provide evidence that material composition played a role in participants' grasping behaviour, affecting both unconstrained and precision grasps. The observed patterns in the distances between the grasp centroid and the object centroid suggest that participants were influenced by the material composition when deciding which side of the object to grasp. This suggests that the weight distribution influenced participants' grasping strategies, leading them to adjust their grip location accordingly.

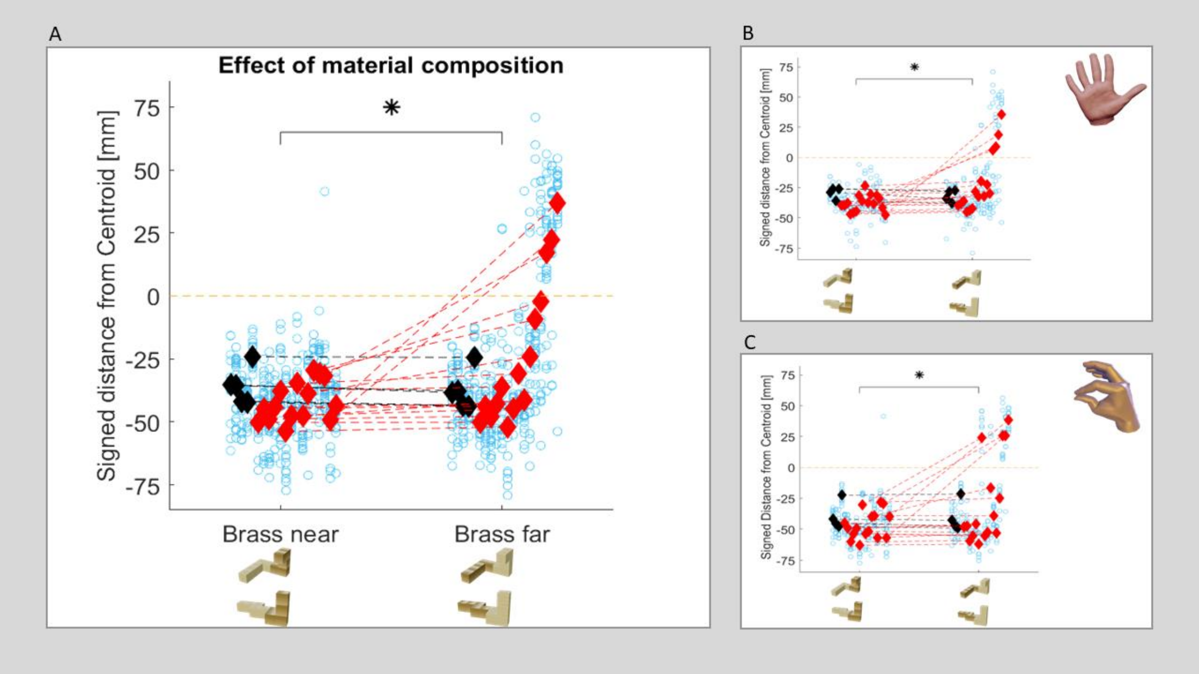

Figure 7. Participants behaviour evaluated on the basis of distance of grasp centroid from centroid of the object and classified on the basis of material composition of the objects. In the visualization, blue dots indicate the distance for each trial, while the yellow dotted line at zero on the y axis represents the position of the object centroid. The left side of each plot displays the distances for the Brass Near objects, while the right side presents the distances for the Brass far objects. Negative values indicate that the contact occurred on the side of the object closest to the participant, while positive values indicate contact on the side farther from the participant. The diamonds indicate the mean distance. To assess within-participants behaviour, subjects with corresponding data are connected by dotted lines, different colours of such lines and diamonds exhibit different types of behaviour within each subject. Red dotted lines and diamonds indicate that the participant executed at least one grasp on the side farther from them, while black lines and diamonds indicate that the participant grasped the object the same way in both sessions. Figure 7A illustrates the overall behaviour for both the unconstrained and precision sessions. Figure 7B and 7C differentiate the behaviour based on the grasping technique.

4.2.2. Grip technique impacts grasping.

Figure 8A displays the distances between the grasp centroid and centroid of the objects for all subjects, categorized on the base of the grip technique participants were instructed to adopt.

The results illustrate an influence of technique in grasping behaviour. The observation of the results from the first plot highlights this influence.

The left side of the plot illustrates the results for the unconstrained session, during which participants had the freedom to choose the number of digits they used for grasping. In this session, the mean distances indicate that the grasp centroid were generally located on the side closer to the participants, as evidenced by the negative values for all subjects. On the right side of the plot, the distances for are shown for the precision grip session, where participants were specifically instructed to use only their thumb and index finger. In this session the mean distances show negative for all the subjects, with three values particularly close to 0.

Closer examination of the lines connecting corresponding subjects in the plot illustrate a slight change in participants’ behaviour when comparing the two sessions. If grasp technique was a factor, all the lines connecting corresponding subjects should have been black, indicating that participants maintained consistent behaviour regardless of grip technique. However, the presence of coloured lines indicates that participants did in some cases change their behaviour based on the instructed grasp technique.

The green lines indicate that three participants grasped the object on the side farther from them more frequently in the unconstrained grip session compared to the precision grip session. Conversely, the red lines highlight the fact that five individuals exhibited a different pattern. They grasped the object from the side farther from them more frequently in the precision grip session compared to the unconstrained grip session. This indicates that for these individuals, the specific instruction to use a precision grip influenced their grasping behaviour.

The results presented in the two plots on the right provide insights into participants' behaviour based on grasping technique, specifically considering the objects' material composition.

In *Figure 8B*, which represents the brass near condition, consistent behaviour is observed among all participants regardless of the grasping technique. The distances between the grasp centroid and the object centroid are negative and have similar values, highlighting the fact that that most people don’t shift the centroid of their grasp by very much in the different condition. This suggests that the material composition of the objects in the brass near condition did not significantly influence participants' grasping behaviour, regardless of whether they used the unconstrained or precision grip technique.

However, in *Figure 8C*, which illustrate the results for the brass far condition, a different pattern emerges. The analysis reveals that participants' behaviour is not as consistent as it was in the brass near condition, and they demonstrate variations in the grasping techniques. The distances between the centroids in this condition are not as similar as in the brass near condition. The lines connecting corresponding participants have different colours, indicating that individual participants altered their behaviour in response to the grasping technique specifically in the brass far condition. The figure displays that for all the three subjects where the mean distance falls on the side closer to them in the unconstrained session, the same occurs in the precision grip session. Additionally, for one participant the mean distance falls in the side farther from them in the unconstrained session but changes side in the precision session.

These finding illustrate that, as expected, participants altered their behaviour on the basis of the instruction they were given, modifying their interaction with the objects during the two sessions.

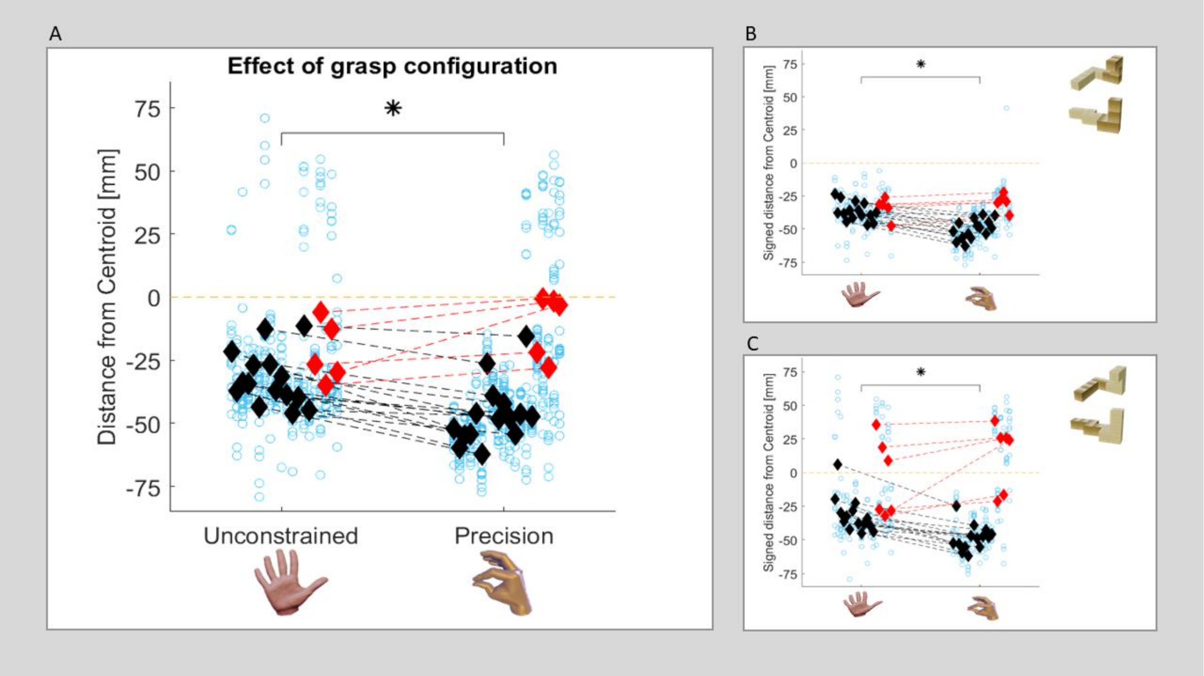

Figure 8. Participants behaviour evaluated on the basis of distance of grasp centroid from centroid of the object and classified on the basis of grasp technique. In the visualization, blue circles indicate the distance for each trial, while the yellow dotted line at zero on the y axis represents the position of the object centroid. Diamonds indicate the mean distance for each participant. The left side of each plot displays the distances for the unconstrained session, while the right side presents the distances for the precision grip session. Negative values indicate that the contact occurred on the side of the object closest to the participant, while positive values indicate contact on the side farther from the participant. To assess within-participants behaviour, subjects with corresponding data are connected by dotted lines, different colours of such lines and diamonds exhibit different types of behaviour within each subject. Red dotted lines and diamonds indicate that the participant grasped the object from the side closer to them more times in the precision grip compared to the unconstrained session. Black lines and diamonds indicate that the participant grasped the object always from the same side, regardless of technique employed. The graph on the left illustrates the overall behaviour for both the Brass near and Brass far objects. The two graphs on the right differentiate the behaviour based on the material composition of the objects.

4.3. Material composition is not the primary determinant factor in grasping.

After recognizing the impact of material composition, the subsequent investigation aimed to examine the extent to which this aspect of an object influences the grasping process. Furthermore, the next objective was to determine if this effect remains consistent when different grip techniques are employed.

To address this question, the approach employed was modified by measuring the distance of the grasp centroid from the CoM rather than the centroid for both sessions of the experiment. ANOVA analysis revealed a significant main effect of material configuration ($F_{1,19} = 92.17$, $p<.001$), a significant main effect of grasp configuration ($F_{1,19} = 14.42$, $p=.0012$), and no significant interaction effect ($F_{1,739} = 2.99$, $p=.08$).

When comparing the distances values within the same material composition objects (brass far or brass near objects), if the CoM is the primary factor behind the preferred interaction in grasping, the values should be similar for both instances. This would indicate that participants adjusted their grasp based on the location of the CoM in the objects. Conversely, if the values differ significantly, it is reasonable to speculate that reach distance, rather than weight, is the more influential aspect in the decision-making process. Specifically, it is expected that if participants behaved similarly for the brass near condition, where the heavier and closer side coincide, then the mean values would cluster around similar values for all subjects. In contrast, it is anticipated that if the distance values will vary more for the brass far condition, where the CoM is located farther from the participants, then the distances for such objects would reach higher values.

After observing the extent to which participants generally rely on material composition when grasping objects, a further investigation addressed whether such effect remains consistent when comparing precision and unconstrained grasping. To explore this further, a comparison between the distances from the CoM both grip techniques was conducted. If the CoM has a greater influence on one technique rather than the other, the results will show lower distances in the technique that is more affected. Conversely, if the effect of material composition is consistent across both techniques, the values will be similar.

A fundamental aspect that needs addressing are the constraints imposed by the precision grip, which limits the ability to generate the same level of force as in unconstrained grasping. Based on this consideration, it is expected that the distance values for the precision grip will be closer to the CoM of the objects. This is due to the restricted use of only two fingers in the precision grip, resulting in a more centralized grasp.

On the other hand, in the unconstrained condition where participants are free to employ more than two fingers and adjust their grip as they prefer, the previous result has shown that participants will tend to employ more than two fingers. This means that it should be taken into account they could "enwrap" the objects from different locations. In this case, when considering the grasp centroid, it is possible that the distances from the CoM of the objects will be lower. This could be because the use of multiple fingers allows for a distributed grasp, potentially resulting in the grasp centroid closer to the centroid of the objects.

4.3.1. Reach distance plays a bigger role than material composition in grasping.

Figure 9A illustrates the results for this analysis.

The left side of the plot illustrates the distances for brass near condition, where the heavier side is also the closest to the participant. On the right side the plot displays the results for the brass far condition, for which the heavier side was the farther one from the participant. As expected, the data exhibit a distinction in values. The mean distances for the two conditions differ noticeably, indicating that participants did not alter their behaviour.

In line with the expectations, the values registered for the brass near condition form a cohesive cluster. This outcome confirms the hypothesis that participants consistently grasp the objects from the side closer to them when such half is also the heavier.

As predicted, the right side of the plot (brass far condition) reveals a distinct and contrasting behaviour. For seventeen out of twenty subjects, the values of mean distance are greater than the highest one registered for the brass near condition. The values illustrate that when the heavier half of the object, and hence the CoM, was located on the side farther from the participants, they generally did not prioritize it as a determinant factor in their grasping behaviour. Instead, they tended to grasp the object from the side that was closer to them, as displayed by the higher values in distance.

Based on these findings, it can be suggested that while material composition does influence grasping behaviour, its impact is not substantial enough to override the influence of other aspects, such as reach distance. Participants generally prioritized grasping the side of the object that was closer to them, regardless of the material composition, suggesting that reach distance is a more dominant factor in their decision-making process.

4.3.2. The same effect is consistent in both precision and unconstrained grip.

Figure 9B displays the distances from the CoM and grasp centroid for all subjects, categorized on grasping techniques.

The plot is divided into two sections. The left side of the plot presents the results for the unconstrained grip session, where participants had no restriction on the number of digits used. On the right side the plot illustrates the distances for the precision grip session, where participants were limited to using only their thumb and index fingers.

The mean distances show similar patterns, with the values for precision grip that appear to be slightly greater.

Based on the data, it can be stated that the effect of material composition is generally consistent across both grip techniques. However, the distances observed in the precision grip session are slightly larger, suggesting that the influence of the CoM was less pronounced during this type of grasp. This finding was somewhat unexpected, as it would be presumable that the distances would be closer to the CoM when performing precision grips, considering that less force is exerted in this grip technique.

As stated in the beginning of the paragraph, it is worth considering the fact that when left without constraints, participants are allowed to employ more than two fingers, and has it has been observed in the first section of the results, that is often the case. This would mean that they could grasp the object by positioning their wrapping their fingers around the object from various points. As a result, it is a possibility that this led to lower values in the distance between the grasp centroid and the CoM of the object. This is because the use of multiple fingers enables a distributed grasp, where the forces and contact points are spread across the object. As a result, the grasp centroid is likely to be closer to the CoM of the objects, leading to lower distances between them.

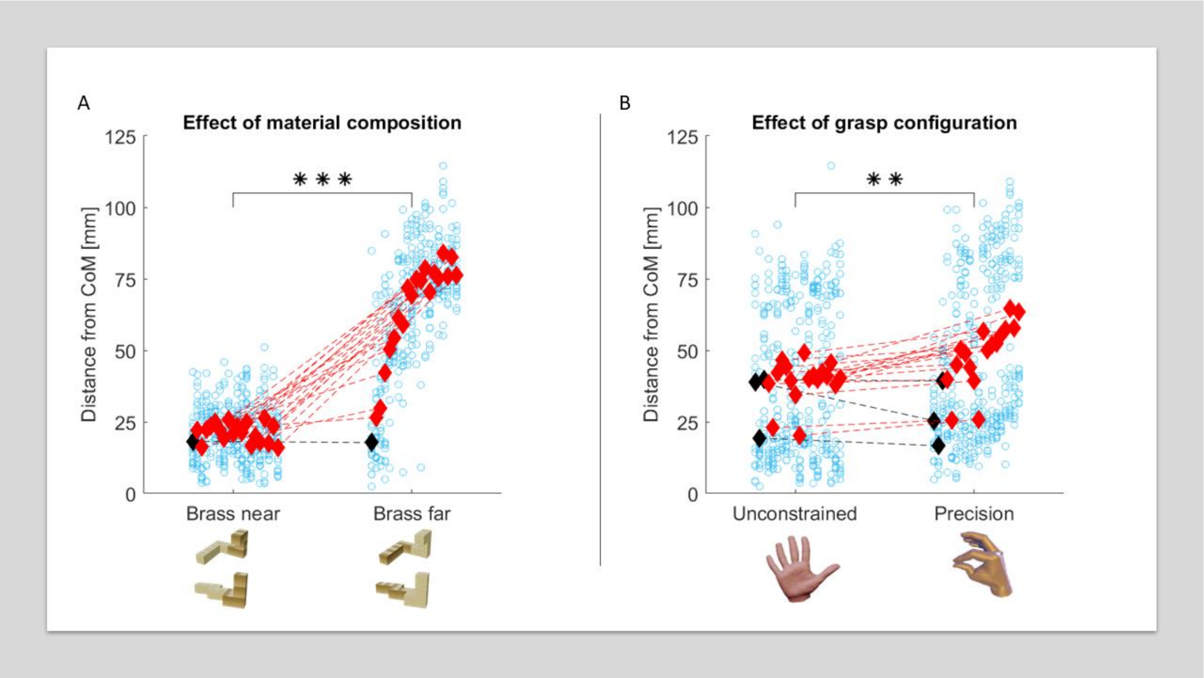

Figure 9. Participants behaviour evaluated on the basis of distance of grasp centroid from center of mass (CoM) of the object. In the visualization, blue dots indicate the distance for each trial, while the yellow dotted line at zero on the y axis represents the position of the object CoM. Diamonds indicate the mean distance for each subject. Corresponding subjects are connected by black dotted lines. In 9A red dotted lines and diamonds indicate that the mean distance is higher for the brass far condition, in 9B they indicate that the distance is higher for the precision condition. The plot on the left depicts the distance classified based on the material composition of the objects, distinguishing between brass near and brass far conditions. The plot on the right shows the distances classified based on grip technique, differentiating between unconstrained and precision conditions.

4.4. Evaluation of the co-registration method

The final section of the results evaluates the effectiveness of the co-registration method developed.

Figure 10 shows the process and final alignments for all the Yale-dataset (30) objects.

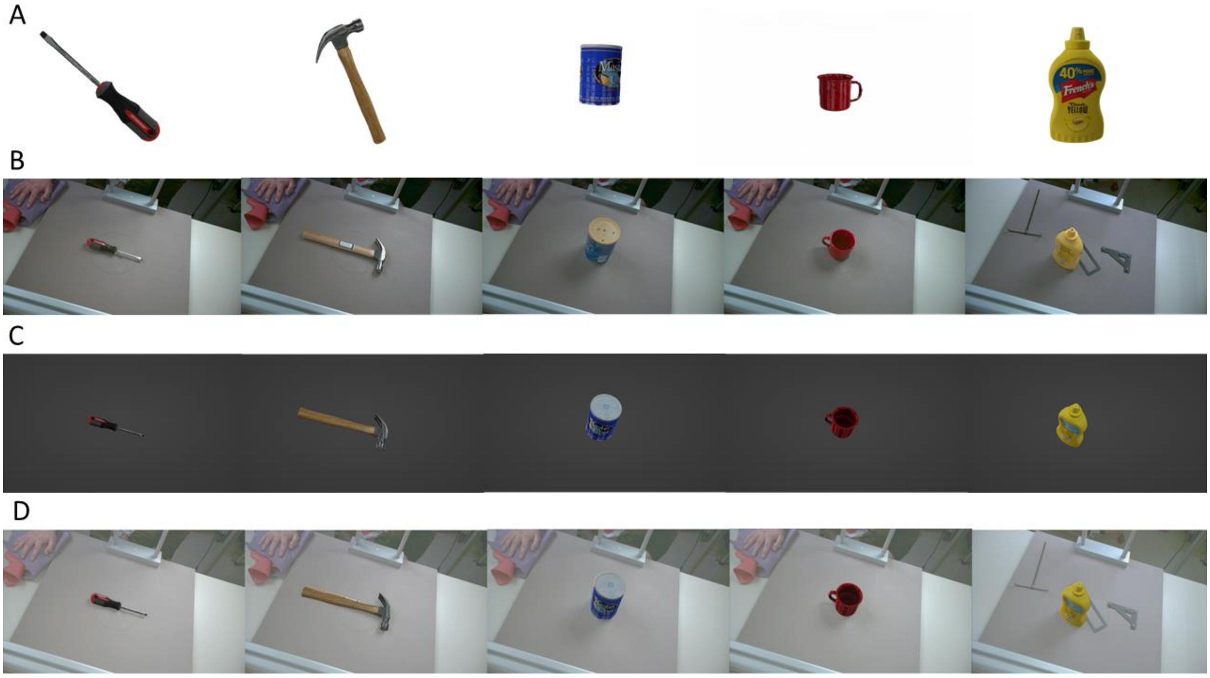

Figure 10. Application of the co-registration method to a subset of five objects from the Yale Dataset (30). 10A depicts all the virtual replica of the objects. 10B shows the first frame of the recording of a grasping task obtained by one of Qualisys Miqus Video cameras. 10C presents the virtual replica of the objects after the application of the co-registration method. They are now positioned and oriented in the same way as their real-world counterparts. The virtual objects are displayed from the same viewpoint as the specific camera. 10D demonstrates the application of the co-registration method for these objects. In the background a frame from the video footage is shown. Overlaid onto each object I its corresponding virtual replica, aligned with the real object using the co-registration technique.

Figure 11 shows the results evaluated using Intersection over Union (31) and a particular application for the precision vs multi-digit study.

Figure 11A presents the results for the objects obtained from the Yale dataset (30). The Intersection over Union (IOU) (31) metric is used to evaluate the alignment between the virtual replica and the real objects, with higher values indicating better alignment. The IOU values demonstrate generally good results, but there are some noticeable inconsistencies across objects. The can, mustard bottle, and cup show high IOU values, exceeding 80%.

This indicates that the virtual replicas align well with these objects. However, the hammer and flat screwdriver provide less successful alignments, with lower IOU values. The discrepancies in the results can be attributed to two factors. Firstly, the location of the markers on the objects plays a role. In the case of the hammer and flat screwdriver, the markers were positioned on one end of the objects. Due to the long physical structure of these objects, even a small error in the co-registration of the markers' positions can lead to a larger discrepancy as you move further away from the markers. This can result in lower IOU values for these objects. Secondly, in the specific case of the hammer, there was a discrepancy between the virtual replica provided by the dataset and the real counterpart. The virtual replica was slightly thicker and longer than the real hammer. This discrepancy can affect the alignment accuracy and contribute to the lower IOU value observed for the hammer.

Figure 11B displays the result for the object used in this study and their virtual replicas appositely created. The bar graph shows much more consistent result, with values similar for all the objects and percentage of IOU all over 90%.

This high level of consistency suggests that the co-registration method employed in this study successfully aligns the virtual replicas with the real object. The IOU values above 90% indicate a strong overlap and similarity between the virtual and real objects, indicating accurate alignment.

The more consistent results in *Figure 11B* can be attributed to several factors. Firstly, the objects used in this study were specifically created with attention to detail, ensuring a closer match between the virtual replicas and the real objects. Additionally, the marker placement on these objects was optimized to enhance the accuracy of co-registration.

Overall, the results depicted in *Figure 11B* demonstrate the effectiveness of the co-registration method in aligning the virtual replicas with the real objects used in this study, with high levels of overlap and accuracy.

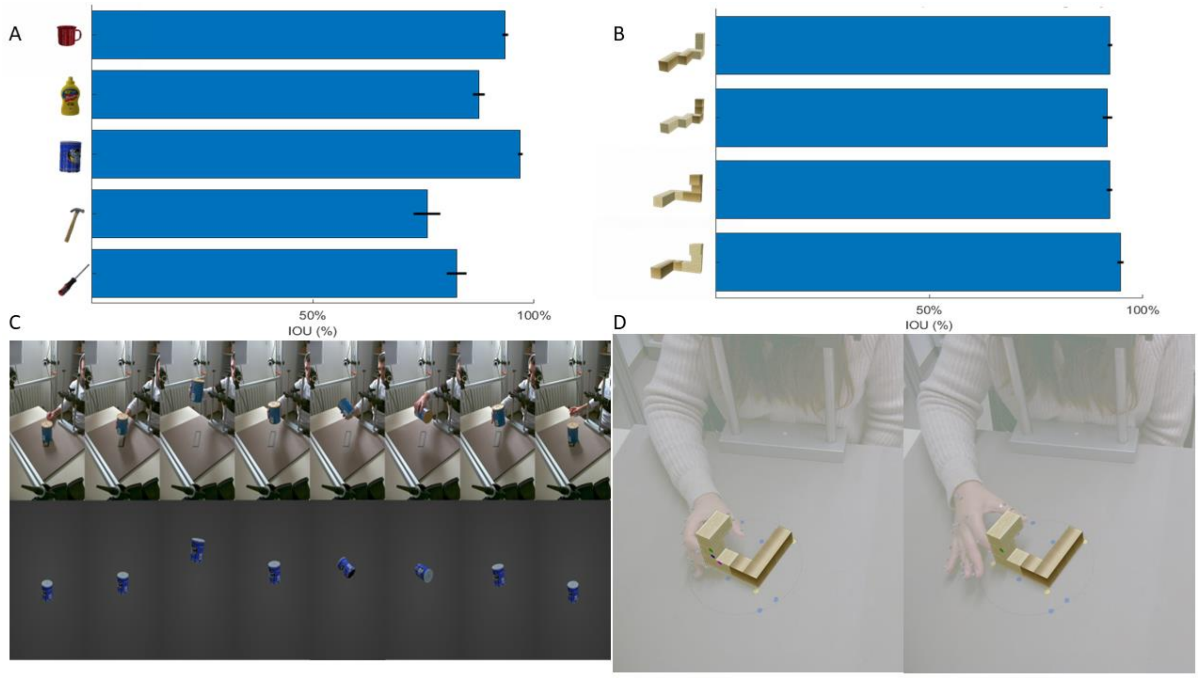

Figure 11. Results in terms of IOU for the co-registration method. 7A shows the results for the objects obtained from the Yale Dataset (30). 7B displays the IOU for the objects used in this study, using the virtual replicas specifically. 7C illustrates an application of the co-registration method for one of the objects from the Yale Dataset (30), with the virtual version of the object replicating the movement of the real counterpart. 7D illustrate an application for the method for a trial in the unconstrained and one for the precision grip session, with the contact points overlaid onto the real footage.

Chapter 5: **DISCUSSION**

This thesis aimed to investigate various aspects of grasping behaviour, with a particular emphasis on comparing multi-digit and precision grip techniques. Building upon previous research, the study also explored the impact of different factors on grasping behaviour. Additionally, a novel method was developed to co-register virtual and real objects, laying the groundwork for future investigations into the effects of virtual environments on grasping behaviour.

To carry out these investigations, an experiment was designed involving 20 participants. The participants were instructed to perform grasping tasks involving a standardized set of objects in two different sessions. In the first session, participants were given the freedom to choose the number of fingers to employ for grasping without any specific instructions. In the second session, participants were specifically instructed to use a precision grip, utilizing only their thumb and index finger.

Overall, the discussion chapter will provide a comprehensive analysis of the presented results, addressing their strength, limitations, and implications. It will also serve as a platform to propose potential avenues for further development and research, contributing to the advancement of knowledge in the field of grasping behaviour.

5.1. Precision Grip is not the natural grip.

The results from the first section of the study indicated that participants rarely employed a precision grip when no specific instruction were given regarding the number of fingers to use for grasping. Instead, they predominantly utilized a multi-digit grip, involving either four or all fingers. This finding suggests that the default gripping technique for participants in unconstrained conditions leaned towards a multi-digit grip rather than a precision grip.

Additionally, the precision grip session revealed that participants had no remarkable difficulties in employing the precision grip when specifically instructed to do so. This indicated that the preference for a multi-digit grip in the unconstrained session was not due to a lack of ability or alternatives.

Instead, participants actively chose to employ a multi-digit grip for a more stable grasping experience.

The relatively rare occurrence of participants employing a precision grip using only two fingers, registered in approximately 10% of the cases, further supports the notion that the decision was not driven by a lack of alternatives. Instead, it suggests that participants perceived the multi-digit grip to be more advantageous or comfortable for their interaction with the objects.

Based on the findings of this study, there are several potential avenues for further investigations. These extensions could help deepen the understanding of grip technique preferences.

To expand on the current findings, it would be interesting to conduct a similar study using a different set of objects. As mentioned in the introduction, precision grip is typically associated with small objects. Therefore, employing objects of smaller size and less complex shape could provide insights into the extent to which such object characteristics influence the preference for precision grip. This investigation would help determine whether the tendency for a multi-digit grasp observed in the unconstrained condition persists even with smaller versions of the objects.

In addition to exploring objects with different characteristics, another extension to consider is a variation in the instructions given to the participants during the grasping tasks. In the current study, participants were instructed to lift the object up and place it back in roughly the same location, regardless of the grip technique employed.

To further investigate the influence of instructions on grasping behaviour, it would be interesting to examine if there are differences in behaviour when participants are asked to perform specific actions with the objects. For example, participants could be instructed to move he object to a different location, rotate it, or place it in a specific orientation. By introducing specific task requirements, it would allow for an assessment of how these instructions impact grip technique selection and the execution of the grasping movements. This extension could provide valuable insights into the flexibility and adaptability of grip techniques in response to different task demands. It would also contribute to understanding the interaction between cognitive processes, task instructions, and motor behaviour during object manipulation. Furthermore, investigating the effect of different instructions could have practical implications in various domains, such as robotics, rehabilitation, and human-computer interaction, where specific actions and tasks are involved in object manipulation scenarios.

5.2. Material composition affects both precision and unconstrained grasping but not as the primary determinant factor.

The second section of the results confirmed a well-known phenomenon: the influence of material composition on grasping behaviour. Previous research ((6), (19) - (22)) has already demonstrated that humans tend to adjust their grasp to position their fingers closer to the CoM when performing precision grips. This finding was replicated in the current study, where participants tended to grasp the objects from the side made of brass. Importantly this effect was observed not only in the precision grip session but also in the unconstrained session, indicating that participants still took material composition into account even when they had the freedom to employ multiple fingers.

It was further observed that, even though material composition played a role in grasping behaviour, it was not the primary determining factor. Instead, reach distance appeared to have a greater influence on the selection of the grasping side. Regardless of the material composition of the objects, participants often chose to grasp them from the side closer to their right hand in the starting position. This observation was consistent across both the unconstrained and precision grip sessions of the experiment. This would suggest that reach distance plays a bigger influence in selecting the grasping side.

These findings suggest that participants prioritize reachability when deciding on the grasping side. The preference for selecting the side closer to the body can be attributed to the reduced reach distance and increased comfort associated with this choice. It is important that this effect was observed irrespective of the specific material composition of the objects, indicating that reachability considerations may override material-related factors in grasping behaviour.

The modest effect of material composition in this study deviates from the findings of another study using the same stimuli under very similar conditions. In their study, Klein et al. (6) found that when the mass distribution of an object was significantly shifted, participants exhibited a notable attraction towards grasp locations closer to the shifted center of mass (CoM) of the object. This finding indicates that participants were able to effectively integrate information about the global shape of the object and its material composition to accurately infer the location of the CoM.

The differences in extent of influence of material composition are likely due to the procedure of the experiment. Specifically, the Klein et al. (6) study employed a larger number of objects in their experiment, which may have provided a wider range of variations in material composition for participants to consider. This broader stimulus set might have led to a stronger influence of material-related factors on grasping behaviour.

Another crucial difference is the presentation of objects with different orientations in Klein et al.'s (6) study. By manipulating the orientation of the objects, participants were likely required to adapt their grasping techniques accordingly. This variation in object orientation introduces additional complexity to the grasping task and may lead to a heightened sensitivity to material composition effects. Examining the impact of different orientations on grasping behaviour can be a valuable extension of this study, as it would provide insights into how each factor contributes to the selection of specific grasping techniques.

Examining the impact of different factors such as material composition, object orientation, as well as object size and shape, can provide a comprehensive understanding of the complex dynamics involved in grasping behaviour.

To enhance the analysis of the interaction between digits and objects during grasping, a possible extension could involve implementing the approach developed by Hartmann et al. (12) and consider contact areas rather than contact points.

The main limitation of the method developed for the identification of the frame of contact in precision grip was its inability to adapt to changes in participant’s grasping behaviour. Occasionally, participants would initially approach the object in a specific manner, establishing contact at a certain frame. However, they would subsequently alter their grasp and modify the contact points. In such instances, the method would erroneously identify the initial frame as the actual contact, failing to account for the participant's later adjustment in grasp. For these specific cases the manual evaluation of the trials was employed. This procedure involved visually inspecting the recorded data to identify the specific frame at which contact between the participant's fingers and the object was first established.

The observation that the mean distances between the grasp centroid and the CoM were similar for both the unconstrained and precision grip sessions, with slightly higher values for the precision grip, suggests an interesting aspect of grasping behaviour. The use of more digits in a multi-digit grip allows for a broader distribution of force around the object, potentially resulting in a grasp centroid that is not as centrally located as in the precision grip.

To further explore this aspect and overcome the aforementioned limitation, a comparison specifically focusing on the center of the thumb and index finger in both the unconstrained and precision grip conditions could be conducted. By isolating the contribution of these two fingers, it would provide insights into how their positioning and distribution of forces are modified when participants perform a precision grip compared to when they are free to use more fingers.

This analysis could explore the role of the thumb and index finger in precision and multi-digit grip and how their coordination and positioning differ between the two gripping techniques. It could help clarify whether the increased use of additional fingers in the multi-digit grip results in a more distributed grasp centroid, potentially affecting the relationship between the grasp centroid and the CoM. Understanding these finger-specific modifications in different gripping conditions can contribute to a more nuanced understanding of the biomechanics and control strategies involved in precision grip and multi-digit grasping.

5.3. Co-registration of Real and Virtual footage

One of the main objectives of this study was to develop a co-registration method that could facilitate investigations of grasping behaviour in virtual and augmented reality environments. The presented results demonstrate the success of the developed method, showing accurate alignment between real and virtual objects. By utilizing tracking data, video footage and virtual replicas of objects, the method effectively replicates the recorded movement of real objects with their corresponding virtual replicas.

This co-registration method offers new possibilities for studying grasping behaviour in virtual and augmented reality settings.

It is worth highlighting that the current implementation of the co-registration method is based on post processing of recorded data, rather than real-time streaming. The next logical step in the development of the method would be to extend its capabilities to handle real-time data streams. By achieving real-time co-registration, researchers would gain the ability to directly investigate grasping behaviour in virtual environments as it unfolds. One aspect to keep in mind is the potential latency discrepancy in real-time streams, as it can have a significant impact on the accuracy and timing of recorded data. Minimizing this obstacle is crucial for conducting studies involving Virtual and Mixed realities, and efforts should be made to address and reduce latency as much as possible in order to ensure reliable and precise results.

Enabling real-time co-registration would open up new avenues for studying and analysing grasping behaviour in virtual environments. Researchers could observe and analyse participants' grasp movements and interactions with virtual objects in real time, allowing for immediate feedback and adjustment of experimental conditions. This would enhance the ecological validity of studies by capturing the dynamics and subtleties of grasping behaviour as it occurs naturally.

Real-time co-registration could also facilitate the development of interactive virtual environments that respond to participants' grasping actions in real time. This would enable the creation of virtual training simulations, virtual reality games, and other applications that require immediate and responsive interactions with virtual objects.

An interesting avenue for research would be the application of the co-registration method to grasping in Augmented Reality. AR offers the unique advantage of overlaying virtual objects onto the real world, creating a blended environment where individuals can interact with both real and virtual elements.

With the ability to modify the appearances of virtual objects in AR, researchers can explore various factors that influence grasping behaviour, such as object colour, texture, size, and weight. By systematically manipulating these factors, they can study how participants adapt their grasping strategies and hand-object interactions in response to the virtual object's visual and physical properties. Studies have addressed the material weight illusion in the real world (32) and the size-weight illusion in Augmented reality (33) as well as the Virtual weight illusion (28). Further development of the method here presented could turn out to be useful for further research on these phenomena.

However, it is important to note that achieving real-time co-registration poses technical challenges, including the need for efficient data processing, accurate tracking systems, and robust algorithms. These challenges would need to be addressed to ensure the reliability and effectiveness of the real-time co-registration method.

5.4. Potential further applications in various sectors

The incorporation of the suggested development and extensions, combined with further research in the field, could potentially generate valuable results with different applications. Various sectors stand to benefit from the results of such research.

Rehabilitation would be a sector that could benefit from a clearer understanding of the cognitive and biomechanical mechanism underlying the selection of optimal gripping techniques. This knowledge could contribute to the development of more advanced and effective rehabilitation strategies for individuals with limb impairments. For example, by understanding how different grip techniques and object properties affect grasping, rehabilitation professionals can tailor therapy programs to target specific motor skills and functional abilities. This may involve designing exercises and interventions that focus on improving precision grip for individuals who require fine motor control, or promoting multi-digit grips for those who need to generate more force in their grasp. Additionally, gaining a comprehensive understanding of the biomechanical mechanism involved in both precision and multi-digit grasping would be critical in the advancement of upper limb prosthetics.

Another sector that would benefit from similar research is robotics. A deeper understanding of grasping behaviour could help develop more realistic and accurate artificial hands. By studying how humans naturally grasp objects and identifying the mechanical trait of different gripping techniques, researched can improve the design and functionality of robotic hands, making them more capable of performing intricate and precise tasks. Moreover, gaining insights into the underlying motivation behind the selection of one gripping technique over another can have profound implications in the field of artificial intelligence. Understanding the cognitive process and the objects properties involved in grasping can help inform the development of intelligent robotic systems. By combining this knowledge with artificial intelligence, robots can autonomously adapt their gripping strategies based on the specific task and object properties, leading to more efficient and effective interactions with the environment.

Furthermore, the findings from this research could have implications in fields such as human-computer interaction and virtual reality. The development of the co-registration methods presented here extends beyond grasping and can find application in various research areas involving interactions with objects in various research areas involving interactions with objects in virtual or mixed reality environments.

In the field of human-computer interaction, the co-registration method can enhance the user experience by providing more accurate and realistic interactions with virtual objects. For example, in virtual training simulations, users can benefit from a more immersive and realistic grasping experience, which can improve their learning and performance in virtual environments. This can have applications in fields such as virtual training for surgical procedures, industrial simulations, and virtual rehabilitation exercises.

In virtual reality, the co-registration method can enhance the realism and immersion of virtual environments. By accurately aligning virtual objects with real-world objects and their interactions, users can have a more intuitive and natural experience in virtual reality. This can improve the sense of presence and embodiment, making virtual reality applications more engaging and effective. For example, in virtual games or virtual design applications, users can interact with virtual objects in a more realistic and natural manner, enhancing their overall experience.

In summary, the potential applications of this research extend beyond the scope of the current study. By further exploring the suggested developments and extensions, advancements in rehabilitation, robotics, human-computer interaction, and virtual reality can be made, leading to significant advancements in these sectors.

Chapter 6: **CONCLUSION**

In this thesis, I investigated natural, unconstrained grasping behaviour. The primary objective was to compare the two gripping techniques—multi-digit and precision grip—and to determine whether precision grip is the default grip employed by humans when no constraints are imposed. Additionally, the study investigated the impact of material composition on grasping behaviour and evaluating its influence in both precision and unconstrained conditions. Finally, a novel method for the alignment of virtual and real objects was developed.

To ensure a fair comparison between these techniques, the study distinguished two conditions: unconstrained and strictly precision conditions.

The results illustrated that when participants were given the freedom to choose their gripping technique without constraints, they predominantly employed a multi-digit grip. This finding confirms the initial expectation that precision grip is not the natural grip, despite a significant portion of the grasping literature focussing on it.

In the introduction of this thesis, previous research on grasping behaviour was discussed. This included studies that investigated how object properties, such as shape, size, and material composition, influence grasping. The role of material composition in grasping was given special attention.

The results of this study revealed that material composition does indeed have an impact on grasping behaviour. However, it was observed that while material composition influences grasping, it is not the primary determining factor. Other aspects, such as reach distance, also play a significant role. Interestingly, the effect of material composition was observed in both precision and multi-digit grasping, suggesting its influence is not technique specific. Further developments in this area of research could delve into the specifics of how material composition affects grasping behaviour in the two techniques. Additionally, conducting a more comprehensive investigation that includes different tasks for the participants to execute, could provide valuable insights into the differences in behaviour when individuals are guided by explicit instructions. This would contribute to a deeper understanding of the complex interplay between various factors that influence grasping behaviour.

Furthermore, the introduction of this thesis has presented the emerging field of grasping in virtual environments. This area of study offers fascinating and exciting possibilities, including the use of augmented reality, to investigate how various properties of objects impact grasping behaviour.

The co-registration method presented in this study lays a solid groundwork for exploring the application of grasping in virtual environments. He integration of AR technologies could provide valuable insights into how different object properties affects grasping behaviour, combining different subjects presented in this study.

In conclusion, this thesis delved into the intricate nature of grasping behaviour by exploring the comparison between multi-digit and precision grip, investigating the role of material composition, and developing a co-registration method for virtual environments. These investigations contributed to the existing knowledge on grasping behaviour and paved the way for further research in this field. By shedding light on the complexities of human behaviour and providing a foundation for future studies, this thesis has advanced our understanding of grasping and its implications across various domains.

Based on the groundwork laid out in this thesis, I am eager to embark on further research to delve deeper into the complexities of human behaviour in grasping. By conducting more comprehensive investigations, I aim to uncover novel insights into the cognitive and biomechanical mechanisms underlying grasping behaviour. This knowledge can then be utilized to drive innovations and advancements in fields such as rehabilitation, robotics, artificial intelligence, human-computer interaction, and virtual reality. Through my upcoming PhD research, I aspire to contribute to the development of more advanced and effective strategies in rehabilitation, the design of more realistic and accurate robotic hands, and the enhancement of human-computer interactions in virtual environments. I am excited about the potential impact that this research can have across various sectors and the opportunity to push the boundaries of our understanding of grasping behaviour.

BIBLIOGRAPHY

(1)'Precision Grip - an Overview | ScienceDirect Topics'. Accessed 25 June 2023. https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biology/precision-grip.

(2)Cesari, Paola, and Karl M. Newell. 'The Scaling of Human Grip Configurations'. *Journal of Experimental Psychology: Human Perception and Performance* 25, no. 4 (1999): 927–35. https://doi.org/10.1037/0096-1523.25.4.927.

(3)Johansson, R. S., and G. Westling. 'Roles of Glabrous Skin Receptors and Sensorimotor Memory in Automatic Control of Precision Grip When Lifting Rougher or More Slippery Objects'. *Experimental Brain Research* 56, no. 3 (1 October 1984): 550–64. https://doi.org/10.1007/BF00237997.

(4)Gonzalez, Claudia L. R., and Melvyn A. Goodale. 'Hand Preference for Precision Grasping Predicts Language Lateralization'. *Neuropsychologia* 47, no. 14 (1 December 2009): 3182–89. https://doi.org/10.1016/j.neuropsychologia.2009.07.019.

(5)Sharma, Neelima, and Madhusudhan Venkadesan. 'Finger Stability in Precision Grips'. *Proceedings of the National Academy of Sciences* 119, no. 12 (22 March 2022): e2122903119. https://doi.org/10.1073/pnas.2122903119.

(6)Klein, Lina K., Guido Maiello, Vivian C. Paulun, and Roland W. Fleming. 'Predicting Precision Grip Grasp Locations on Three-Dimensional Objects'. *PLOS Computational Biology* 16, no. 8 (ago 2020): e1008081. https://doi.org/10.1371/journal.pcbi.1008081.

(7)Maiello, Guido, Marcel Schepko, Lina K. Klein, Vivian C. Paulun, and Roland W. Fleming. 'Humans Can Visually Judge Grasp Quality and Refine Their Judgments Through Visual and Haptic Feedback'. *Frontiers in Neuroscience* 14 (2021). https://www.frontiersin.org/articles/10.3389/fnins.2020.591898.

(8)Klein, Lina K., Guido Maiello, Roland W. Fleming, and Dimitris Voudouris. 'Friction Is Preferred over Grasp Configuration in Precision Grip Grasping'. *Journal of Neurophysiology* 125, no. 4 (April 2021): 1330–38. https://doi.org/10.1152/jn.00021.2021.

(9)Zatsiorsky, Vladimir, and Mark Latash. 'Digit Forces in Multi-Digit Grasps'. *Sensorimotor Control of Grasping: Physiology and Pathophysiology*, 25 June 2009, 33–51. https://doi.org/10.1017/CBO9780511581267.004.

(10)Santello, Marco, and John F. Soechting. ‘Force Synergies for Multifingered Grasping’. *Experimental Brain Research* 133, no. 4 (1 August 2000): 457–67. https://doi.org/10.1007/s002210000420.

(11)Feix, Thomas, Javier Romero, Heinz-Bodo Schmiedmayer, Aaron M. Dollar, and Danica Kragic. ‘The GRASP Taxonomy of Human Grasp Types’. *IEEE Transactions on Human-Machine Systems* 46, no. 1 (February 2016): 66–77. https://doi.org/10.1109/THMS.2015.2470657.

(12)Hartmann, Frieder, Guido Maiello, Constantin A. Rothkopf, and Roland W. Fleming. ‘Estimation of Contact Regions Between Hands and Objects During Human Multi-Digit Grasping’. *Journal of Visualized Experiments: JoVE*, no. 194 (21 April 2023). https://doi.org/10.3791/64877.

(13)Naceri, Djallil, Alessandro Moscatelli, Marco Santello, and Marc Ernst. ‘Multi-Digit Position and Force Coordination in Three- and Four-Digit Grasping’, 101–8, 2014. https://doi.org/10.1007/978-3-662-44193-0_14.

(14)Pei, Dingyi, Parthan Olikkal, Tülay Adali, and Ramana Vinjamuri. ‘Dynamical Synergies of Multidigit Hand Prehension’. *Sensors* 22, no. 11 (January 2022): 4177. https://doi.org/10.3390/s22114177.

(15)‘Virtual Finger’. https://www.cs.cmu.edu/afs/cs/user/sbk/www/thesis/virtual-finger.html.

(16)Budgeon, Mark K., Mark L. Latash, and Vladimir M. Zatsiorsky. ‘Digit Force Adjustments during Finger Addition/Removal in Multi-Digit Prehension’. *Experimental Brain Research* 189, no. 3 (August 2008): 345–59. https://doi.org/10.1007/s00221-008-1430-9.

(17)Gorniak, Stacey L., Vladimir M. Zatsiorsky, and Mark L. Latash. ‘Hierarchical Control of Static Prehension: II. Multi-Digit Synergies’. *Experimental Brain Research* 194, no. 1 (March 2009): 1–15. https://doi.org/10.1007/s00221-008-1663-7.

(18)Lukos, Jamie, Caterina Ansuini, and Marco Santello. ‘Choice of Contact Points during Multidigit Grasping: Effect of Predictability of Object Center of Mass Location’. *The Journal of Neuroscience* 27, no. 14 (4 April 2007): 3894–3903. https://doi.org/10.1523/JNEUROSCI.4693-06.2007.

(19) Desanghere, Loni, and Jonathan J. Marotta. ‘The Influence of Object Shape and Center of Mass on Grasp and Gaze’. *Frontiers in Psychology* 6 (2015). https://www.frontiersin.org/articles/10.3389/fpsyg.2015.01537.

(20)Paulun, Vivian C., Karl R. Gegenfurtner, Melvyn A. Goodale, and Roland W. Fleming. ‘Effects of Material Properties and Object Orientation on Precision Grip Kinematics’.

Experimental Brain Research 234, no. 8 (1 August 2016): 2253–65. https://doi.org/10.1007/s00221-016-4631-7.

(21)Kleinholdermann, Urs, Volker H. Franz, and Karl R. Gegenfurtner. ‘Human Grasp Point Selection’. *Journal of Vision* 13, no. 8 (25 July 2013): 23. https://doi.org/10.1167/13.8.23.

(22)Paulignan, Y., V. G. Frak, I. Toni, and M. Jeannerod. ‘Influence of Object Position and Size on Human Prehension Movements’. *Experimental Brain Research* 114, no. 2 (1 April 1997): 226–34. https://doi.org/10.1007/PL00005631.

(23)Voudouris, Dimitris, Eli Brenner, Willemijn D. Schot, and Jeroen B. J. Smeets. ‘Does Planning a Different Trajectory Influence the Choice of Grasping Points?’ *Experimental Brain Research* 206, no. 1 (1 September 2010): 15–24. https://doi.org/10.1007/s00221-010-2382-4.

(24)Lederman, Susan J., and Alan M. Wing. ‘Perceptual Judgement, Grasp Point Selection and Object Symmetry’. *Experimental Brain Research* 152, no. 2 (1 September 2003): 156–65. https://doi.org/10.1007/s00221-003-1522-5.

(25)Roby-Brami, Agnès, Nezha Bennis, Mounir Mokhtari, and Pierre Baraduc. ‘Hand Orientation for Grasping Depends on the Direction of the Reaching Movement’. *Brain Research* 869, no. 1 (30 June 2000): 121–29. https://doi.org/10.1016/S0006-8993(00)02378-7.

(26)Chessa, Manuela, Guido Maiello, Lina Klein, Vivian Paulun, and Fabio Solari. ‘Grasping Objects in Immersive Virtual Reality’, 1749–54, 2019. https://doi.org/10.1109/VR.2019.8798155.

(27)Oprea, Sergiu, Pablo Martinez-Gonzalez, Alberto Garcia-Garcia, John A. Castro-Vargas, Sergio Orts-Escolano, and Jose Garcia-Rodriguez. ‘A Visually Realistic Grasping System for Object Manipulation and Interaction in Virtual Reality Environments’. *Computers & Graphics* 83 (1 October 2019): 77–86. https://doi.org/10.1016/j.cag.2019.07.003.

(28)Maehigashi, Akihiro, Akira Sasada, Miki Matsumuro, Fumihisa Shibata, Asako Kimura, and Sumaru Niida. ‘Virtual Weight Illusion: Weight Perception of Virtual Objects Using Weight Illusions’. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, 1–6. CHI EA ’21. New York, NY, USA: Association for Computing Machinery, 2021. https://doi.org/10.1145/3411763.3451842.

(29)Dandu, Bharat, Irene A. Kuling, and Yon Visell. ‘Where Are My Fingers? Assessing Multi-Digit Proprioceptive Localization’. In *2018 IEEE Haptics Symposium (HAPTICS)*, 133–38, 2018. https://doi.org/10.1109/HAPTICS.2018.8357165.

(30)Yale-CMU-Berkeley (YCB) Object and Model Set was accessed from https://registry.opendata.aws/ycb-benchmarks.

(31)'Intersection Over Union IoU in Object Detection Segmentation', 28 June 2022. https://learnopencv.com/intersection-over-union-iou-in-object-detection-and-segmentation/.

(32)Paulun, Vivian C., Gavin Buckingham, Melvyn A. Goodale, and Roland W. Fleming. 'The Material-Weight Illusion Disappears or Inverts in Objects Made of Two Materials'. *Journal of Neurophysiology* 121, no. 3 (March 2019): 996–1010. https://doi.org/10.1152/jn.00199.2018.

(33)Rohrbach, Nina, Joachim Hermsdörfer, Lisa-Marie Huber, Annika Thierfelder, and Gavin Buckingham. 'Fooling the Size–Weight Illusion—Using Augmented Reality to Eliminate the Effect of Size on Perceptions of Heaviness and Sensorimotor Prediction'. *Virtual Reality* 25, no. 4 (1 December 2021): 1061–70. https://doi.org/10.1007/s10055-021-00508-3.

(34)Schot, Willemijn D., Eli Brenner, and Jeroen B. J. Smeets. 'Robust Movement Segmentation by Combining Multiple Sources of Information'. *Journal of Neuroscience Methods* 187, no. 2 (30 March 2010): 147–55. https://doi.org/10.1016/j.jneumeth.2010.01.004.

(35)Ambike, Satyajit, Florent Paclet, Vladimir M. Zatsiorsky, and Mark L. Latash. 'Factors Affecting Grip Force: Anatomy, Mechanics, and Referent Configurations'. *Experimental Brain Research* 232, no. 4 (April 2014): 1219–31. https://doi.org/10.1007/s00221-014-3838-8.

(36)Community, B. O. (2018). *Blender - a 3D modelling and rendering package*. Stichting Blender Foundation, Amsterdam. Retrieved from http://www.blender.org

ACKNOWLEDGMENTS

Finally, I would like to take the time to acknowledge and thank everyone that supported me during this project.
Firstly, I would like to thank my thesis advisor Prof. Chessa, for her continuous support in the last year and for the possibility of pursuing this experience, which changed my life.
Thanks to Guido for being the best mentor I could ask for and for being the most patience person ever, I can’t wait to start working together again!
I will be forever thankful to Roland, for giving me the opportunity of working in your lab, where I couldn’t ask for a better and more welcoming environment, and for all the invaluable advice you gave me during this experience.
Thanks to Frieder for your crucial help and guiding me in everything in this project.
Thanks to Kira, with whom I shared the experience of this project the closest to, sharing both the ups and downs. Knowing you was an immense pleasure, and I can never thank you enough for your help in this experience.
Lastly and especially, thanks to my girlfriend Paula, the most beautiful and important thing that this experience could ever give me. I will never find the right words to thank you enough for enduring me and for always being with me during this journey, that you made unforgettable.

Il grazie più grande va ai miei genitori e mia sorella. Il vostro perenne appoggio è la base senza cui non sarei mai riuscito a raggiungere non solo questo ma nessun altro traguardo raggiunto finora nella mia vita. La speranza di rendervi felici e fieri di me è la più grande motivazione che guida ogni mia scelta e ogni mio sforzo.
Ringrazio i miei nonni, per l’avermi cresciuto e reso la persona che sono ora, grazie alla loro saggezza e ai loro consigli.
Ringrazio tutti i miei zii e cugini, per essermi stati tutti sempre vicini ed essere stati sempre disponibili per qualunque cosa.
Ringrazio infine i miei più cari amici, che ci sono sempre stati e che ci saranno sempre, per aver reso più facili i periodi difficili e indimenticabili quelli più belli. Le innumerevoli serate che spendiamo assieme passando da discorsi profondi a stupidi sono quello che più mi rende felice e che porterò sempre con me.