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Original Research Article

Automated process chain for the individualization and additive manufacturing of daily living aids

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Abstract: This paper presents an innovative approach to design and manufacture individualizable daily living aids for people with disabilities or motoric impairments. The focus is on enhancing autonomy in daily tasks through individualizable daily living aids that can be tailored to the user's anatomy and limitations. Utilizing a combination of Additive Manufacturing (AM), parameterized design, and Artificial Intelligence (AI), a fully automated process chain was developed for individualizing and manufacturing these daily living aids. The process begins with a detailed product development, followed by the extraction of user-specific measurements from video or image data using AI-based image processing techniques. These measurements are passed on to a parametric design model, enabling quick adaptations to individualize the daily living aid. The result is a scalable process chain, where individualized daily living aids can be manufactured on demand, minimizing the need for standard solutions that may not meet the user's needs. The case study focuses on a daily living aid for cutlery, demonstrating the successful integration of the developed process chain from design through production. The results highlight the potential of this automated process chain to improve the quality of life for people with disabilities, providing them with greater access to assistive devices tailored to their requirements.

I. Introduction

People with a disability or motoric impairment face challenges in everyday life. Activities such as unlocking doors, opening bottles and holding cutlery can be difficult. Adaptations to these tools (keys, bottle openers, cutlery) are necessary to enable people to live independently and autonomously. These tools are everyday objects that should be accessible to everyone. There are two options to make this possible:

- Differently, new designed everyday objects
- Modular, individualizable daily living aids that can be attached to the everyday objects or incorporate the everyday object

The advantage of daily living aids is their flexibility. Existing tools can easily be used, even when travelling (e.g. in a restaurant). However, there are not enough suitable daily living aids available on the market. These are often standard solutions in predefined sizes and shapes, which are not sufficient to restore quality of life and independence.

This is where the individualizable daily living aids we have developed, and their manufacturing process come in. Three approaches are used and combined for this purpose: image processing with Artificial Intelligence (AI), parametric design and Additive Manufacturing (AM). AM enables the production of individualized daily living aids that incorporates the user's anatomy and motoric limitations [1]. For individualization, measurements of the body part with which the tool is used (usually hands) are required. The design of the daily living aid is adapted accordingly and manufactured individually.

A parameterized design allows the daily living aid to be quickly and easily tailored to the user's needs [2]. Therefore, the dimensions for individualization are automatically extracted from image and video data using image processing and AI methods.

The combination of AI, parametric design and AM has resulted in a process chain that enables the automated design and manufacturing of individualized daily living aids. To achieve this, we started with a detailed product development including a requirements analysis for the daily living aid. The design of the daily living aid was derived from this. The realization of the design in a parametric design is crucial here. This ensures automated individualization. The parameters needed for individualization result from the product and design development and have to be extracted from image and video data. To analyze image and video data manually takes a lot of time and expertise. Therefore, image processing and AI methods are used. These detect the hand and extract measurements, like width and height. The measurements are then channeled back to the parametric design to create the individualized daily living aid. Because the daily living aid is individualized, it is only manufactured on request. This is why AM is a suitable manufacturing method. The manufacturing of the individualized daily living aid completes the developed process chain.

The process chain was developed based on a cutlery daily living aid. This daily living aid can be attached to a knife, fork or spoon. In this paper, we look at the use case of knives. The product development, image and video analysis, parametric design and the manufacturing process are explained in detail in the following. The focus in this context is on aspects that enable the automation of the process chain and the individualization of the daily living aid.

II. Material and methods

In this section, we describe the methods used in the development of individualized daily living aids, focusing on product development, image processing, parametric design, and AM. The approach integrates various techniques to ensure that the designs are tailored to meet the specific need of users. We begin by outlining the product development process, which is rooted in understanding user's requirements and ergonomics. Following this, we will look at the methods used to extract user-specific measurements from video and image data using AI techniques. To conclude, the parametric design process is described, which enables rapid adaptation of the daily living aid based on the measurements extracted and leads to the AM phase, in which the individualized virtual designs are physical produced.

II.I. Product development

The basis for product development is an understanding of the use and handling of the daily living aid. The requirements for the daily living aid are derived from this. The daily living aid is divided into two parts: the functional part and the human-machine interface. The functional part consists of the knife itself and the anchoring of the knife in the daily living aid. The man-machine interface is represented by the handle. The handle is decisive for the individualization of the daily living aid and therefore the optimum benefit for the user. For this reason, this is the focus of the following section. Usability, accessibility and a comfortable user experience are the most important requirements for the handle. The handle must fit comfortably in the hand, and it must be possible to operate it with minimal force. This requires an ergonomic handle with a haptic surface structure.

To determine the shape of the handle, prototypes of the daily living aid with different handles are designed and manufactured. A cylindrical shape was chosen as the basic design for the handle, as it is very well suited to the knife geometry and the associated physiological posture. Depending on the motoric impairment, a knife is held using a diagonal volar grip or transverse volar grip [3]. These grip types are shown in Figure 1. The shape is extended by two differently curved handle shapes: One of which is positioned in the middle of the handle, making it symmetrical, and the other one has a slightly forward-shifting curve and a narrow end. The curvature of the handle is similar to the anthropomorphic shape of grabbing the hand. For further support when grabbing, another variant is created that includes an attachment to the handle in the form of a non-flexible strap. This allows the daily living aid to be positioned well on the user's hand and prevents the knife from falling out of the hand during use. The four variations described are shown in Figure 2.

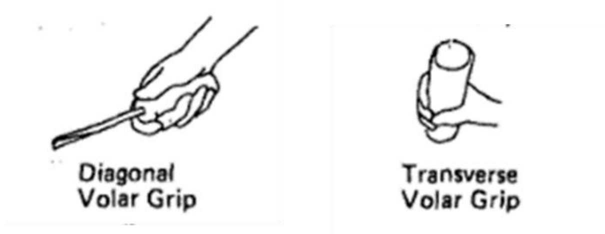

Figure 1: Two types of the volar grip; adapted from [3]

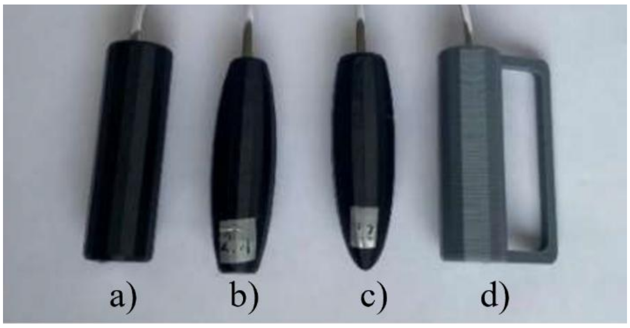

Figure 2: The four design options of the daily living aid: a) cylindrical handle, b) cylindrical handle with a symmetrical curved shape, c) cylindrical handle with a forward shifted curve and a narrow end, and d) cylindrical handle with a non-flexible strap

In a small survey with nine participants with motoric impairment, the different handle shapes of the daily living aid were tested. The group of participants consisted of six men and three women, aged between 20 and 69. Seven of the nine participants have reduced fine motor skills and the other two people have other limitations. The participants were asked the following questions to determine the best shape of the handle:

- How helpful is the shape of the handle?
- How comfortable is the shape of the handle?
- How is the movement to be made with the daily living aid?

The answers and associated subjective experiences of the participants could not be assigned to exact scales. For this reason, the interviews were also evaluated subjectively. The forward shifted curved shape of the handle was identified as the best shape. However, the non-flexible strap was also rated as helpful. This results in a new design of the handle. The symmetric curvature and the non-flexible strap are combined, and this is the basis for the final design of the daily living aid, which is shown in Figure 3.

By using a non-flexible strap, the individualization parameters can be derived directly:

- Width of the hand
- Height of the hand

This is because it is necessary for the hand to fit into the non-flexible strap but not have too much room to slide back and forth easily. This is the crucial factor in achieving the optimum benefit for the user. These two parameters (width and height of the hand) must therefore be individualizable in the design. In addition, these must be automatically extracted from image and video data.

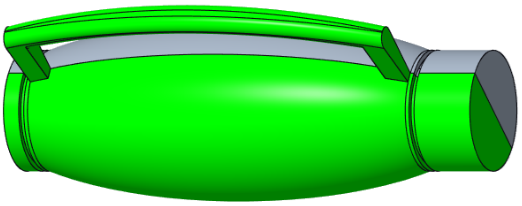

Figure 3: Final design of the handle of the daily living aid. The cylindrical handle is symmetrical shaped and has a non-flexible strap.

II.II. Analyzing the video and image data

During product development, it turned out that the width and height of the hand are necessary for the individualization of the daily living aid. Either video or image data of the hand can be used to extract the measurements. There is only one difference between analyzing video and image data. When analyzing a video, the relevant frames must first be identified. After that, the steps are the same. For this reason, the steps for video processing are described in the following.

The aim is not to require any manual input, but to implement a completely automated analysis of the video data. All steps of the video analysis were implemented in Python and are shown in Figure 5.

In the first step, it must be ensured that the algorithm can translate the measurement points into length in cm for the subsequent steps. For this, an ArUco marker is in the background of every video. The ArUco marker is a binary, square fiducial marker. It consists of a black border and an inner binary matrix. The inner matrix acts as an identifier. The ArUco marker has a fixed size and can be detected automatically. [4] This allows the edge length in pixels of the detected ArUco marker to be used to calculate the ratio of pixels to cm. The ratio is crucial to determine the real width and height of the hand.

The next step is hand recognition and landmark detection. The open-source algorithm 'MediaPipe Hand Landmarker' was used in this study [5]. The algorithm consists of a palm detection model and a hand landmarks detection model. First, the hand is recognized, and the input image is cropped accordingly. The landmarks are then detected in the cropped image. [5] Figure 4 shows the landmarks that the algorithm can detect. The detected landmarks are used to select the video frames that show the hand from the side and from above. The distance between landmarks 5 and 17 is utilized for this purpose. The side view of the hand corresponds to the minimum distance between landmark 5 and 17. The view of the hand from above corresponds to the maximum distance between landmark 5 and 17.

The maximum distance between landmarks 5 and 17 also matches the width of the hand.

Next, the height of the hand is extracted from the side view of the hand. First, the selected frame is cropped because the height of the hand in the knuckle area is required. Afterwards conventional methods of image processing are used. The cropped frame is converted into a grayscale image and a Gaussian filter is applied.

The contrast is adjusted to clearly separate the hand from the background. The separation is then achieved using Otsu Thresholding. Possible small gaps within the hand and small errors in the background are eliminated by morphological closing. The outline of the hand can now be identified. The Canny algorithm for edge detection is used for this purpose. The last step is to calculate the distance between the upper and lower edge of the hand. This distance is still in pixels and is converted using the ratio of pixels to cm, which was previously determined using the ArUco marker.

The extracted measurements of the hand are the input for the parametric design and the starting point for the individualization.

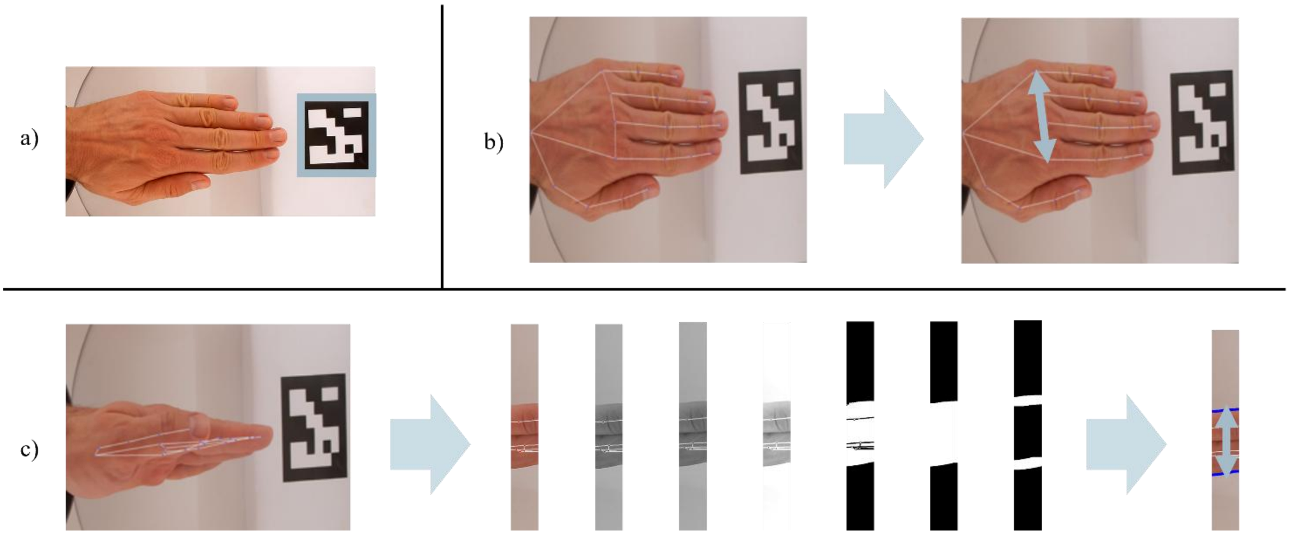

Figure 5: Process steps of the video analysis: a) detection of the ArUco marker, b) determining the width of the hand by finding the maximum distance between landmark 5 and 17, and c) determining the height of the hand by converting the image into a grayscale image, using a Gaussian filter, adjusting the contrast, applying Otsu thresholding, applying closing and using Canny edge detection.

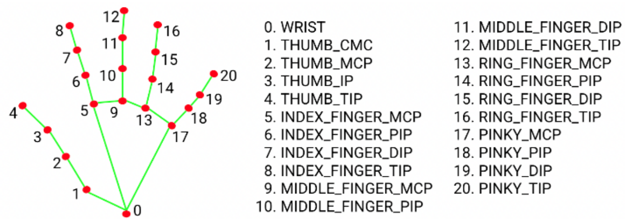

Figure 4: Landmarks detected by 'MediaPipe Hand Landmarker' [6]

II.III. Individualization through parametric design

Based on the extracted hand measurements through the image analysis, an individualized part should be generated. This should happen fully automatically to ensure scalability of the process chain. Therefore, a solution using the parametric design options of the CAD-software PTC Creo (PTC Inc., Boston, USA) was created. Hereby, three main functionalities, namely, skeleton, parameter and family table were used. All of them are described in the following.

Skeleton

A skeleton forms the base in parts or assemblies. It is a non-solid element which is used to define the main structure of the part or assembly. The structure is defined through planes und axes. By importing the skeleton in a part or assembly all planes and axes defined in the skeleton are available in the part or assembly. Using these planes and axes as references in the design process, the construction depends on the skeleton. Changing the parameters in the skeleton therefore affects the construction. [7]

Parameter

Parameters are used to define dimensions of the skeleton or parts instead of fixed values. Hereby, also computational relationships can be used and not only one by one relationship from a parameter to a dimension. For example, the parameter length can be assigned to a specific dimension d1 with an arbitrary formula:

$$d1 = \frac{length}{2}$$

Using this functionality, also complex relationships between dimension can be described in a generic way. Additionally, these parameters are accessible through an API, which allows a fully automatic workflow. [7]

Family Table

In addition to parameterization regarding dimensions, parts or assemblies can also be parameterized regarding their features. Different versions of a part or an assembly can consist of different sub features or subparts. In order to organize such cases, family tables are used. In these tables different versions of a part or an assembly are defined. Each row of a family table represents a version of a part or assembly whereas a sub feature or subpart is represented by a column. Each field in the table indicates by YES or NO if the version includes the specific sub feature or subpart. [7]

The previous explained concepts of skeleton, parameter and family table are used to create a parametrize the model of a daily living aid for knifes. The height and width of hand are used as parameters to define the distance between the base planes of the skeleton. The construction is based on these two planes, which means that an adjustment of the parameters leads to an adjustment of the entire construction. Although the handle design is the most promising, each person has preferences. Hence, a family table allows a configuration of the daily living aid. However, three different options are available, a version with a stop, a version without anything and the version with a handle. The concept of the construction is depicted in Figure 6.

II.IV. Additive manufacturing of the daily living aid

To make individualization scalable for many products and users, the entire process workflow must be automated. Feature extraction is already automated by the algorithm. In a final step, the features must be transferred to the parameterized CAD model and the additive manufacturing process can then be started.

Feature Transfer

Once the daily living aid has been designed parametrically and the features have been extracted using the developed algorithm, the features must be transferred to the CAD system. For this purpose, an automated process was developed that transfers the features to the CAD system. The Python library creopyson was used for this. This library enables script-based access to the functionalities of PTC Creo. The previously described tools Skeleton, Parameter and Family tables are also supported. This library makes it possible to save the generically constructed model as an individualized STL-file based on the output of the algorithm.

Production

The individualized virtual part can then be translated into a physical part using AM technologies. Compared to subtractive processes, additive processes have the great advantage that no additional tools are required for production, and it is possible to manufacture complex geometries with minimal effort. The component is built directly from the desired material in the final geometry. The material is available as a filament, powder (plastic/metal) or photopolymer resin. During the manufacturing process, only the amount of material is required that corresponds to the volume of the digital part. Some processes require additional support structures to support critical geometries. After the manufacturing process, the support structures must be removed. [8,9]

A Fused Deposition Modeling (FDM) printer, namely the Ultimaker S5 (Ulitmaker, Utrecht, Netherlands) was used to produce the daily living aids. These are widely used and easy to operate. This also enables rapid prototyping when developing new everyday aids. The printed daily living aid is shown in Figure 7.

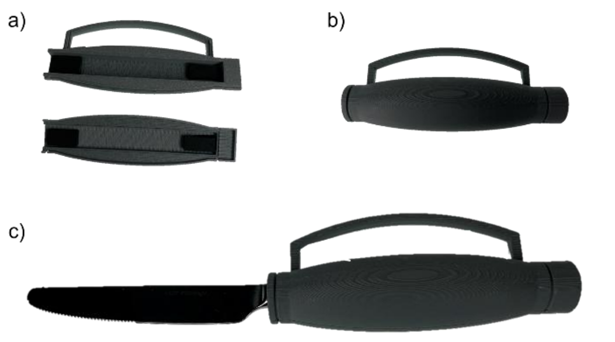

Figure 7: Daily living aid printed with a FDM printer. a) The two parts of the daily living aid. b) The assembled daily living aid. c) The daily living aid with an inserted knife.

With the help of the Cura-Engine (Ultimaker, Utrecht, Netherlands) an automated slicing of the STL-file was realized which provides the production code for any printer. If a printer is connected to the network, the production file is automatically forwarded to the printer so that the production process starts without the need for manual intervention. The corresponding print parameters must be defined once in advance for certain component types. According to this workflow, the only manual step in creating an individualized daily living aid is the video recording. For a better overview, the process chain is shown in Figure 8.

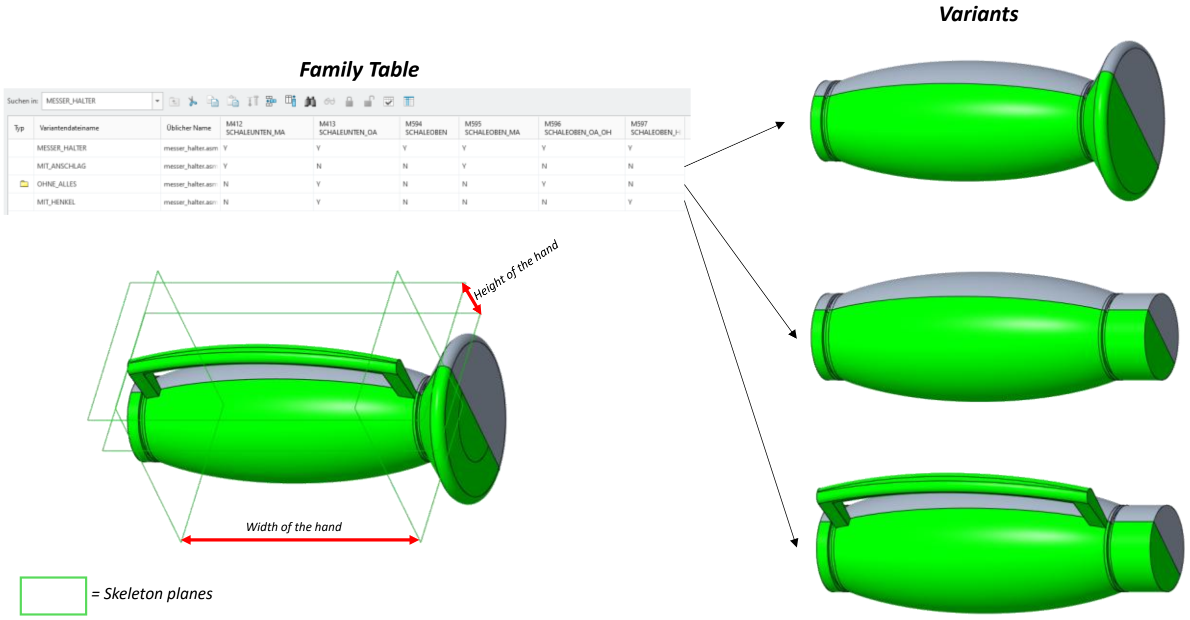

Figure 6: Parametrized Construction realized in PTC Creo. By using the concepts skeleton, parameter and family table individualized version of the base part can be automatically generated.

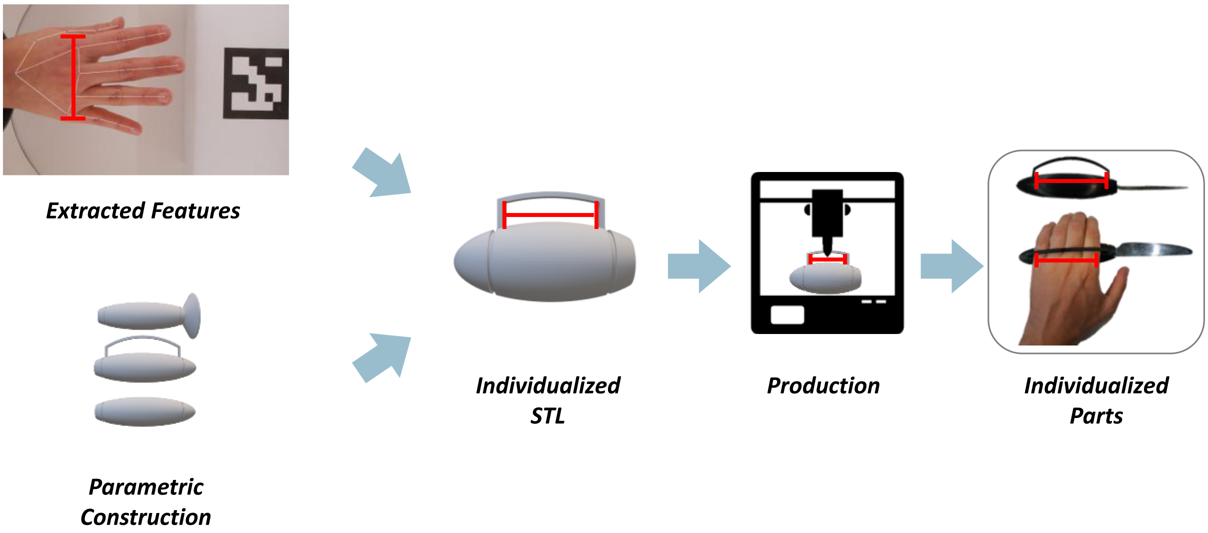

Figure 8: Automatic AM process chain to generate an individualized daily living aid based on an input video and a parametric construction.

III. Results and discussion

We have successfully established a functioning automated process chain for the individualization of daily living aids. This process chain is designed to be expandable, allowing for future enhancements and adaptations. However, more complex daily living aids also lead to a more complex process chain. This can make it particularly difficult to keep the process chain fully automated in the future.

A significant advantage of our approach is the successful combination of parametric design, AI methods and AM for the purpose of individualization.

However, we encountered challenges related to the accuracy of detecting the height of the hand. The process steps implemented are sensitive to the positioning of the hand which can lead to errors in the individualization process. One example of this is the positioning of the thumb. If it is not at the same height as the rest of the hand, the height of the hand cannot be determined correctly. This is shown in Figure 9. Robustness of the image and video analysis should therefore be a focus of further development. The sensitivity to the positioning of the hand was determined during a visual evaluation of the video data set after the automated, AI-based analysis. An objective, quantitative evaluation is not possible. As the video data was recorded at a trade fair, the exact dimensions of the recorded hands are missing. For this reason, only a visual, subjective analysis is possible. This and the robustness of the image and video analysis should be a starting point for the further development of the process step. This is because a video data set with associated ground truth is necessary to ensure the applicability of the analysis in the operational environment.

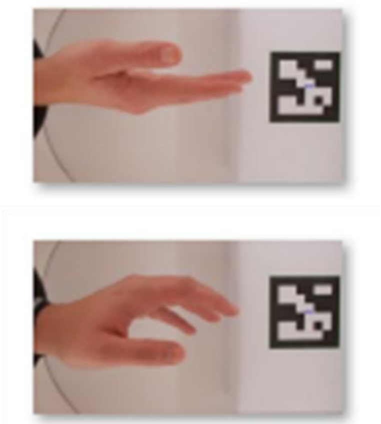

Figure 9: Positions of the thumb that lead to an incorrect calculation of the height of the hand.

Despite the challenges, the use of the image and video data and the AI-based analysis developed has a major additional advantage. The recordings can be made independently by the user at home using a mobile phone. This advantage could also be utilized for other areas of application. The field of application of individualized hand orthoses is particularly worth mentioning. In this case, customization is based on a 3D scan that has to be taken by an orthopedic technician. The process steps developed for the automated evaluation of the image and video data could also be extended and adapted to this application in the future.

The utilization of AM enables rapid availability of individualized daily living aids. To achieve reliable AM outcomes to maintain the quality and functionality of the final product, process parameter optimization would be the next step. In addition, the influence of material selection on the use and benefit of the daily living aid is of interest.

The use of FDM printing for the production of daily living aids offers the possibility of producing the daily living aid not only by a manufacturer, but also on site in a rehabilitation clinic or physiotherapy practice. This can significantly shorten the provision time and facilitate integration into everyday life. Importantly, our developed process chain enables the ordering of individualized daily living aids without the need for in-person visits to medical supply stores. This enhances accessibility for users and a shift towards user-centered solutions in the field of assistive devices.

IV. Conclusions

With our process chain, we were able to show that completely automated design individualization and additive manufacturing of daily living aids is possible. This is achieved by combining AI methods, parametric design and AM.

This process chain can now be used as a starting point for the development of new daily living aids. This can also include everyday aids for other parts of the body. Because the individual components of the process chain can be easily exchanged and extended. In addition, the selection of daily living aid, the providing of users' video data and the ordering of the daily living aid could also take place in an app in future. This would simplify the supply process.

The developed process chain and their possible extensions can improve the quality of life of people with disabilities or motoric impairments and enable them to participate in everyday activities.

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Author's statement

Conflict of interest: Dorit Haasis and Christian Felgner are stakeholders and employees of TGU Enabl3D. Informed consent: Informed consent has been obtained from all individuals included in this study.

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