INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.214

Exploratory Analysis of Adaptively Morphing Handle Forms for Load Transfer Use Cases

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Abstract

Through optimal design of the human machine interfaces, especially the hand-handle contact surface, high usability of hand-operated products can be achieved. The complexity of the user specific hand anthropometry has to be considered in the design of load transfer handles. Use case optimized, personalized, and adaptively morphing handles aim at fulfilling this requirement. To identify design parameters for adaptive handles an experimental design for systematic analysis of user and use case requirements is proposed and evaluated showing the potential of adaptive handles.

Keywords: user-centred design, anthropometry, ergonomics, experimentation, adaptivity

1. Introduction

Hands and the tasks performed by them differ greatly. As a result, handle designs are equally diverse. This paper builds on previous research and studies, proposes an experiment design, and discusses first results for adaptive handle design guidelines. An adaptively morphing handle developed and designed at Institute for Engineering Design and Industrial Design (IKTD) of University of Stuttgart is utilized. This work's greater goal is to support the development of a new generation adaptive handle based on new functional principles compared to the existing one. Therefore, users' hand anthropometric data and use case specific forms are analysed. Based on a use case study, a test stand is designed to isolate load transfer use cases and to identify the corresponding handle forms. The second goal of this work is to find a method for the standardised comparison of different handles.

The paper starts by briefly describing the state of the art of anthropomorphic handle design in chapter 2. Then, the applied methods and the design of the test stand and experiment are described in chapter 3. The analysis of the measurements and adaptive handle forms follows in chapter 4. Consequentially, indications for adaptive morphing handle design guidelines are identified in chapter 5. The paper concludes with a discussion and an outlook in chapter 6.

2. State of the art

Following a user centred design approach the diverse anthropomorphic hand dimensions, as described in chapter 2.1, serve as a basis for handle design. The approaches described in chapter 2.2 differ in their degree of adaption to individual users and use cases.

2.1. Hand anthropometry

The interface of a handle has to match to the anthropometry of the human hand as well as the use case in its layout, shape, and surface, after Seeger's product gestalt model (2005). This assumption implies that the complexity of the human hand is essential for the development of handle shapes. The literature

is characterized by three approaches to the description of the human hand. The most basic description of the hand is done by determining the contour dimensions of the hand (Garrett, 1971; DIN 33402-2, 2020). The main approach to the human hand is through the kinematic model of the musculoskeletal system (An et al., 1992; Cobos et al., 2008; Liu and Zhan, 2013; Yang et al., 2006). For the description of the hand, movement is mapped with different degrees of freedom of the individual mobility of finger limbs and the palm of the hand. The last option for describing the hand is through the form of the skin surface area. For this purpose, an approximation via basic geometric bodies was made through an ellipsoidal representation of human hand anthropometry by Buchholz and Armstong (1991). An alternative method for the determination of the reference geometry was carried out by Rogers et al. (2008). In this research the digitization of the landmarks was measured with a motion analysis system. Wei et al. (2020) and Stillfried et al. (2010) use computed tomography or magnetic resonance images for referencing the construction line within the computer aided model.
An interconnection of the approaches to describe the human hand anthropometry both user-related and use case dependent are not represented in the current studies. For the design of product forms - especially those representing a counter form to the hand, such as handles - the approaches of the hand dimensions, the kinematic model, and the hand shape have to be integrated.

2.2. Ergonomic handle design approaches

Bullinger (1994) laid a groundwork for ergonomic handle design, by deriving three standardized sizes from human hand measurements after DIN 33402 (2020) and load transfer studies. These handles are geometrically described by one length and two diameters, resulting in convex rotationally symmetric forms. These generally fit common proportion hands independently from the use case.
Use case specific handles can be seen on pretty much any handheld or manually operated product. Ranging from bicycle grips to electric tool handles with integrated functional elements, these handles are generally optimized for their intended user group and main use case, see Maier (2008). The next evolutionary step is the personalized handle for an individual user. Optimized for either one specific or multiple use cases, these grips are adapted to the user once. Approaches aiming at realizing these personalized handles vary: Eksioglu et al. (2004) derive the ideal diameter for load transfer handles from hand sizes. In different sports users modify their grips to adapt them to their individual needs. Complex hand geometry data can be derived via image analysis (Eichinger 2020). Deriving a personalized handle form from user anthropometric data is currently the state of the art.
In this lies the research gap, when aiming for ideal usability. Usability can be defined as the extent to which a product enables a specific user to reach a specific goal effectively, efficiently, and satisfactorily within a specific use context DIN EN ISO 9241-11 (2018). Existing approaches focus on individual users and use cases, however, both may vary within a use context. Therefore, the product requires some adaptivity to the users and use cases. For this work an adaptive handle that adapts to both different users and use cases in real time was developed. It was first introduced by Lassmann et al. (2019) and is based on work by Janny (2018) and soft robotics functional principles after Follmer et al. (2012). The design has since been enhanced by the authors to allow load transfers occurring in real life applications. The adaptive handle morphs its form passively following the user's hand dimensions and use cases by varying the stiffness of a granulate-filled flexible shell using pneumatics. Its 42 mm diameter cylindrical base form can be compressed or protruded for currently up to 12 mm each. This functionality goes beyond state of the art handle designs.

3. Methods

This work focusses on the objective measurement of efficiency as one part of the usability evaluation of (adaptive) handles. Therefore, the pressure on the hand-handle contact surface is compared to the effective load transferred through the handle. In a first step use cases are identified. Based on this, an experimental design for exploring use case specific handle forms and comparing different handles is proposed. This method aims at laying the groundwork to examine Lassmann et al.'s (2019) basic hypotheses stating that (1) an adaptive handle's usability compares better to a personalized or standardized handle's and (2) does so by maximizing hand-handle contact surface size for load intensive use cases.

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3.1. Use case identification

A rollator (or walker) is chosen as use context. Due to motor and sensory limitations, rollator users' comfort and load transfer efficiency are potentially improved by an adaptive handle.

User specific handle forms can be captured utilizing the adaptive handle and 3D scanning its morphed form. But to furthermore capture use case specific handle forms, individual use cases within the use context need to be identified. Dragging backwards (V1), pushing forward (V2), lift up (V3), support standing (V4), turning left (V5), turning right (V6), and over-edges lift (V7) were observed as use cases beforehand via interviews. The use cases are shown in figure 1. Subsequently, the following work focusses on developing an experimental setting to isolate these use cases and capture corresponding adaptively morphed handle forms.

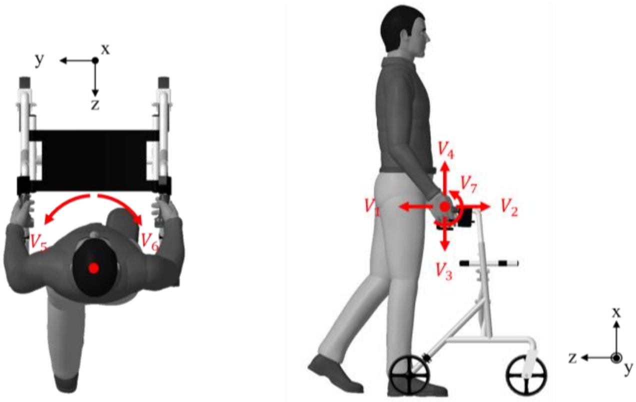
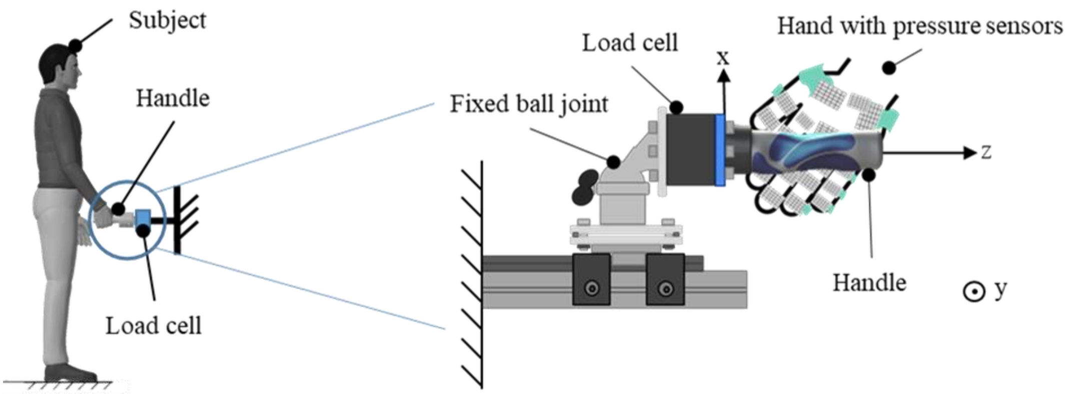


Figure 1. Use case dependent load transfer cases derived from rollator usage

3.2. Experiment for use case specific handle forms analysis

To examine these various load transfer use cases individually and in a neutral setting a test stand is designed. Figure 2 shows a global (a) and a detailed view (b) of the test stand. The handle is interchangeable and can be fixated in various positions to imitate numerous use cases.



a) b)

Figure 2. Test stand global configuration (a) and detailed view (b)

The test stand is designed similarly to existing test stands for handle applications (see You, 2005), but offers flexible positioning of the handle. A load cell (ME-Messsysteme K6D80) with nominal force of 2 kN and a nominal torque of 100 Nm records the force and torque behaviour in spatial direction. The force distribution or pressure in the hand-handle contact surface is measured with the TekScan Grip™ system with a sensel density of .062 1/mm^2 (40 1/sqin) and a total thickness of 1.1 mm (0.15 mm sensor thickness plus 0.95 mm supporting fabric). Comparing the effectively transferred loads and the pressure on the subject's hand allows for an objective usability evaluation in the efficiency domain. The pressure on the hand-handle contact surface and the use case specific dynamic loads are recorded at a sampling rate of 10 Hz to detect main loads. To avoid

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superimpositions of the application, the measurements were carried out in a clamped test environment. The test stand height is adapted to the subjects' body height, to ensure constant and comfortable angles in the subjects right shoulder, elbow, and wrist. Therefore, the hand position remains the same while the use case specific load directions vary. The use case specific forms of the adaptive handle are captured using a structured light 3D scanner (Artec Eva) with an accuracy of ±0.1 mm. For this, the handle remains positioned in its fixture within the test stand.
A single-subject study was conducted to evaluate the test stand and the method for the exploratory analysis of adaptively morphing handle forms for load transfer use cases. In this study five handle designs were compared, see Figure 3. The first three handle designs are the ergonomic standard handles considering user anthropometry by Bullinger (1994), handles Standard-L, -M, and -S. Additionally, a personalized handle was casted to fit the subject's relaxed closed hand with a maximum contact surface. Lastly, the same adaptive handle as in the predecessor study is examined. In this case, it is not adapted to just the subject, but adapts to each use case individually. By slowly applying the forces, the handle morphs its form according to the use cases loads and hardens, so the load is transferred without further deformation.

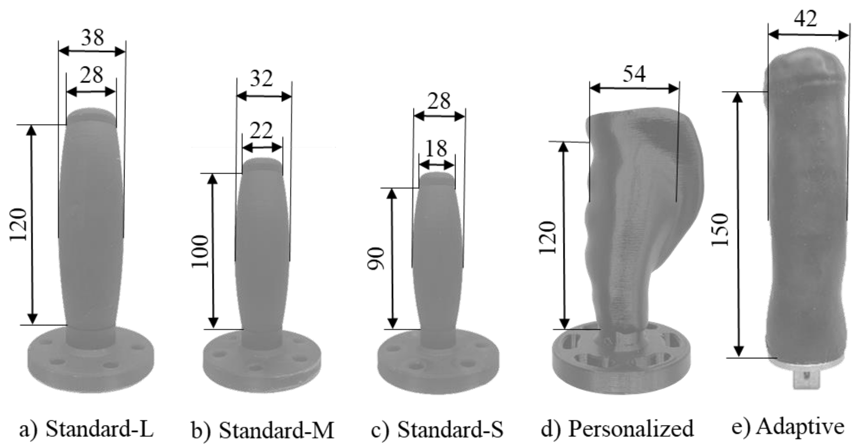

Figure 3. Handle designs used for the study: three sizes standard handle (a-c), handle personalized for the subject (d), adaptive handle (e)

The subject's characteristics and anthropometric hand data, as shown in Table 1, are required as a basis. The data was acquired by a survey, geometric measurements, and photographs.

Table 1. Subject characteristics and hand size following DIN 33402-2 specifications

Subject data and hand dimensions					
Gender:	m	Hand width:	102 mm	Ring finger length:	80 mm
Age:	28	Palm length:	118 mm	Small finger length:	67 mm
Hand size:	200 mm	Index finger length:	75 mm	Thumb length:	75 mm
Palm width:	93 mm	Middle finger length:	83 mm		

4. Results

The following results serve as evaluation of the study design, in regard to scaling it up for a larger study. This allows for systematically comparing of different handles by objective measurements as well as capturing user and use case specific morphed handle forms. Furthermore, first use case specific, adapted handle forms are explored and analysed in chapter 4.3.

4.1. Use case specific load transfers

During the experiment the effectively transferred forces and torques at the fixed ball joint were observed. For each use case a main load was significant for performing a use case with a low impact of the sub loads, see Figure 4a. For a load transfer handle mounted to a rollator, each load behaviour at

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the clamping represents a specific use case. Figure 4a displays the force and torque behaviour of the handle design Standard-M for the use case lift up (V3). For this use case the sub loads can be defined as the forces in the direction of the axes Y, Z and any torques. The characteristic load is in the direction of the X-axis. Figure 4b displays the main force and torque curves of the handle design Standard-M for all investigated use cases. The load behaviours in opposite directions have approximately the same amount of transferred loads.

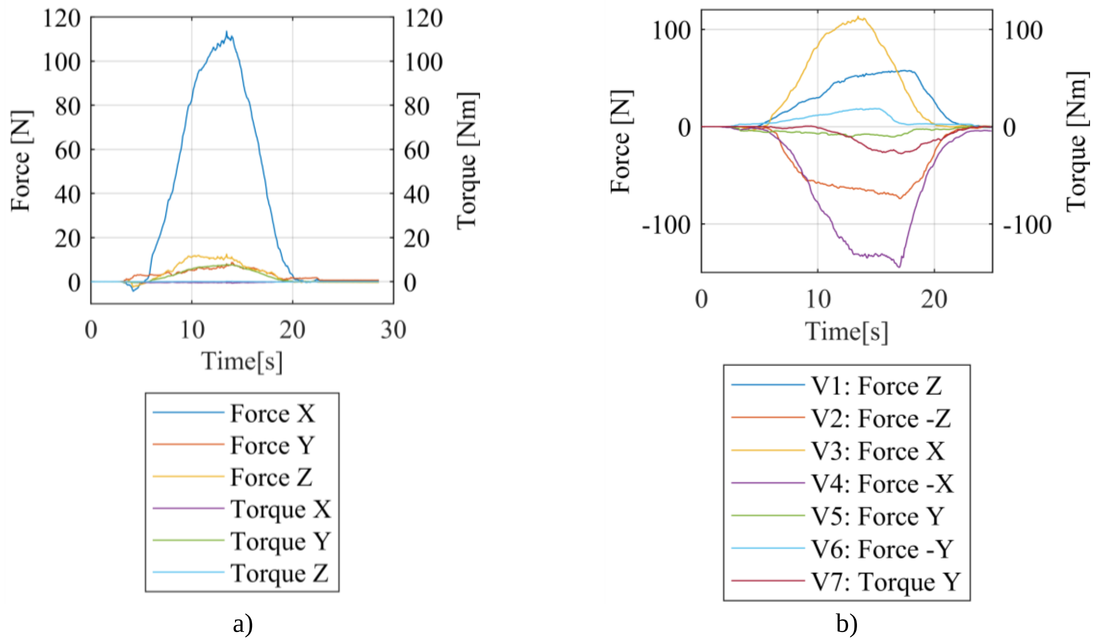

Figure 4. Comparison of the force and torque behaviour of the handle Standard-M for the use case V3 lift up (a) and comparison of the use case dependent force and torque behaviour of the handle Standard-M (b)

To compare the handle designs for specific use cases, the main loads are standardized on a certain reference level, see Figure 5. At the time stamp of the intersection of the reference level and the use case specific main load the pressure at the hand-handle contact surface can be investigated. Through this method the subjective user sensation has no influence on the results of the test. The time stamps of the reference points are located within the increasing signal edge of the main load. Figure 5 contains an adequate sample of the established reference point of the use case: dragging backwards (V1) for all handle designs at a reference level of 30 N.

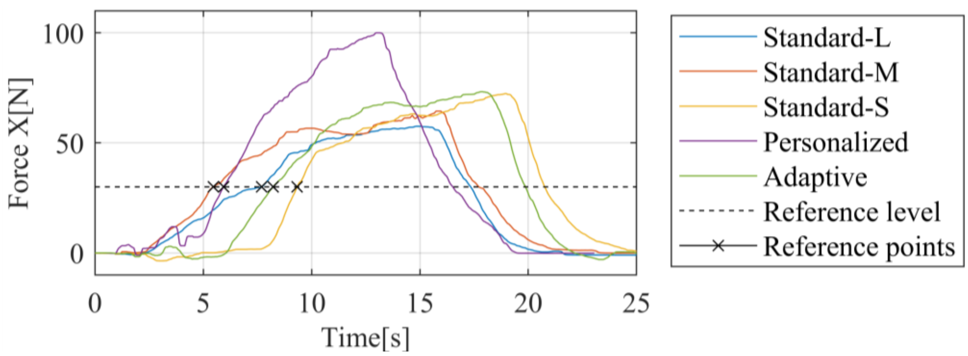

Figure 5. Comparability of the load behaviour for the determination of the reference points for the pressure at the hand-handle contact surface of the use case dragging backwards (V1)

The maximum effectively transferred load varies by use case, even for the same subject. To enable systematic comparison of different handle designs, reference levels of the main load have to be standardized. Table 2 shows the quantified reference levels for this study.

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Table 2. Main load direction and quantification by use case

Use case	Experiment no.	Main Load	Reference point
Dragging backwards	V1	Force Z	30 N
Pushing forward	V2		-30 N
Lift up	V3	Force X	30 N
Support standing	V4		-30 N
Turning left	V5	Force Y	5 N
Turning right	V6		-5 N
Over edges lift	V7	Torque Y	5 Nm

4.2. Grip force measurements and handle form comparison

For these specific reference levels of transferred load, contact surface (A), mean pressure (MP) and peak pressure (PP) at the hand-handle contact surface were measured. The results are shown in Table 3. A comparison of contact surface size shows no clear distinction between the handles across all use cases. For movements in ±Z direction (use cases V1 and V2), the contact surface is largest across all handles, since there is minimum normal force leading to a decoupling between hand and handle. Across all use cases, the adaptive handle shows low mean and peak pressure. The load is therefore distributed more equally on the hand-handle contact surface than for the other examined handles. Despite a close form fit to the subject's hand, the mean and peak pressure are high for the personalized handle. Of all three standard handles Standard-L's size fits the subject's hand best following Bullinger, (1994) and DIN 33402-2 (2020) classification. This is also shown in a lower mean and peak pressure.

Table 3. Contact surface, mean and peak pressure by handle and use case

Handles		V1	V2	V3	V4	V5	V6	V7	Mean	σ	unit
Std.-L	A	3,905	3,857	3,505	3,025	2,913	3,105	3,121	3,347	407	[mm^2]
	MP	.14	.09	.11	.05	.06	.06	.15	.09	.041	[N/mm^2]
	PP	1.67	.43	1.37	.17	.81	.48	2.73	1.09	.898	[N/mm^2]
Std.-M	A	3,825	4,065	3,441	3,121	2,177	3,073	3,201	3,272	610	[mm^2]
	MP	.11	.10	.09	.06	.06	.13	.34	.13	.097	[N/mm^2]
	PP	.96	.57	.58	.25	.26	2.23	8.82	1.95	3.103	[N/mm^2]
Std.-S	A	4,465	4,513	3,345	3,201	3,713	3,521	3,777	3,791	517	[mm^2]
	MP	.31	.16	.09	.07	.12	.07	.41	.18	.133	[N/mm^2]
	PP	5.19	.98	.48	.34	.78	.35	9.79	2.56	3.628	[N/mm^2]
Pers.	A	4,481	4,273	3,361	3,841	3,841	1,968	3,969	3,676	833	[mm^2]
	MP	.26	.15	.10	.10	.20	.04	.41	.18	.125	[N/mm^2]
	PP	7.38	2.14	.75	.32	.85	.12	6.34	2.56	3.024	[N/mm^2]
Adapt.	A	4,033	3,409	3,281	4,161	3,841	3,089	3,777	3,656	402	[mm^2]
	MP	.08	.05	.05	.05	.07	.03	.11	.06	.026	[N/mm^2]
	PP	.97	.19	.40	.18	.64	.11	1.15	.52	.413	[N/mm^2]

Figure 6 shows a pressure map comparison example and visually emphasizes the difference between the handles for one use case (V2). A blank pressure map shows the sensor size comparison. The sensors are attached to the subject's right hand. The better the standardized handle size fits the subjects' hand size, the lower the mean and peak pressure for this use case. For other use cases this differs, indicating that a convex handle form with specific length is not adapted to the user's hand in enough detail. The personalized handle's contact surface is large but mean and peak pressure are still high. While the contact surface size is similar on a high level, mean pressure and peak pressure is significantly lower for the use case dependent adapted handle form. Therefore, geometrical parameters of the handle surface need to be examined on a more detailed level. This indicates the necessity for design guidelines for user and use case specific handles as discussed in chapter 5.

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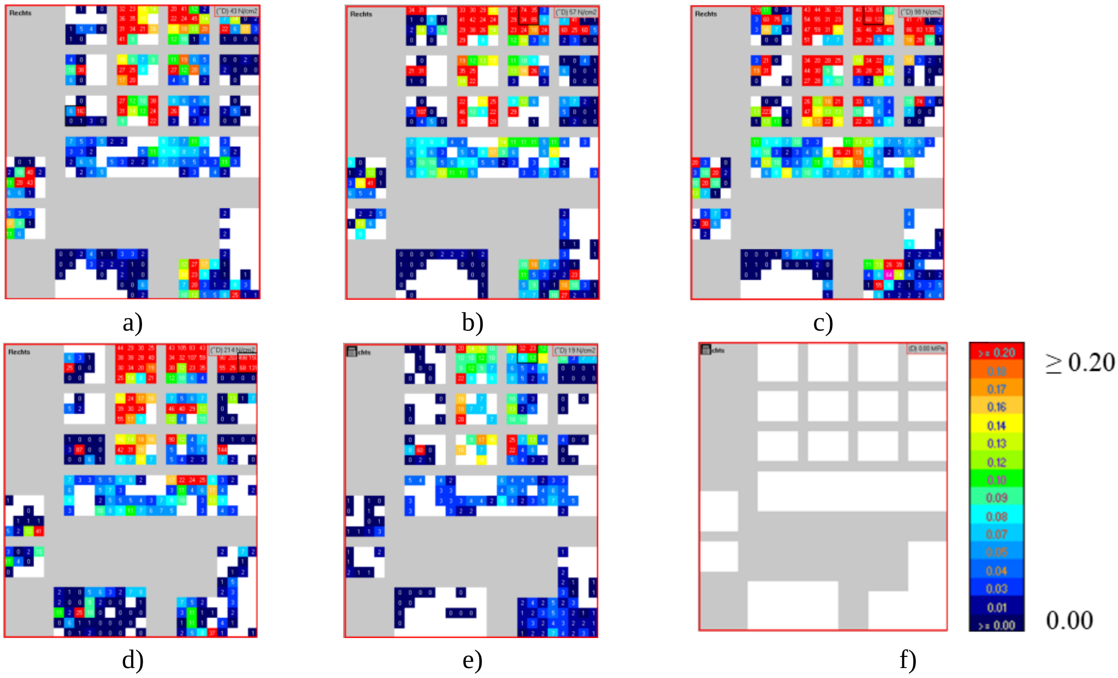
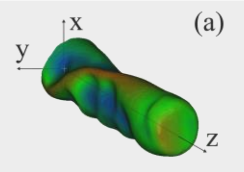
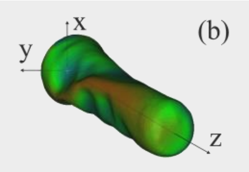
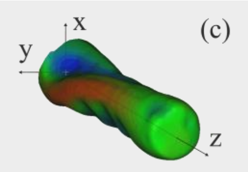
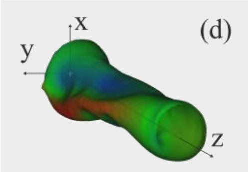


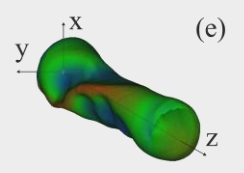
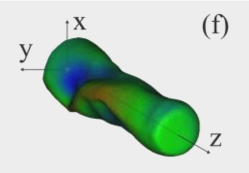
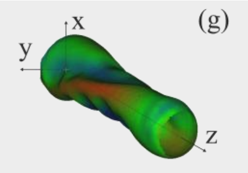
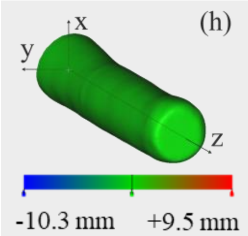
Figure 6. Pressure map comparison example by handle form for use case V2: Standard-L (a), -M (b), and -S (c), personalized (d) and adaptive (e) handle, blank pressure map and legend (f)

4.3. Use case specific handle forms

To analyse the use case specific form of the adaptive handle, the following method was integrated in the experiment design. After each execution, the handle form was scanned. The resulting point clouds were converted to meshes and smoothed using a Laplace filter with 20 iterations and a weighting factor of 0.5 to ensure surface smoothness close to the physical handle. The use case specific handle forms were then compared to the un-deformed adaptive handle, which was processed identically. The resulting handle forms as well as the base adaptive handle are shown in Table 4.

Table 4. Morphed adaptive handle forms with radial deformation from un-deformed handle depending on use case and transferred load direction

Use case	V1	V2	V3	V4
Load direction	Z	-Z	X	-X
Grip Form				

Use case	V5	V6	V7	None
Load direction	Y + Rot(-X)	-Y + Rot(X)	Rot(-Y)	None - un-deformed handle
Grip Form				

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The adapted forms provide maximized contact surfaces vertically to the transferred load (to enable form closure) and parallel to the transferred load (for frictional coupling). These coupling surfaces are formed by individually distinguishable finger and thumb indentations of -6.9 to -10.3 mm. Table 4 (a) shows these indentations for the distal phalanxes parallel to the Z-forces for frictional coupling. Comparing (a) and (b) shows form closure in Z and -Z-direction respectively at the supporting "wing" (highlighted in red) and at the thumb indentation at the handle base. The adaptive handle also forms a convex support for the palm and knuckles, adapting to the subject's hand, as seen in (f). The protrusion of the aforementioned wing varies between 5.6 and 9.4 mm, as does its shape and position on the handle side. These descriptions serve as basis for the design guidelines for adaptive handles, discussed in the following.

5. Discussion and design guideline indications

In the following, adaptive handle design guidelines derived from use case specific forms are discussed. This focusses on the handle's layout and form as three-dimensional shape in regards to Seeger's (2005) gestalt model. Accordingly, a product consists of a layout, shape, colour and surface, and graphics. These sub-gestalts are influenced by user anthropometric data and use cases, as shown in Figure 7. The optimal adapted forms can be quantitatively described by parameters. These forms can then frame the functionality of future adaptive handles after extensive research. Design parameter quantifications are still limited, since they are derived from use case specific forms in a single-subject study.

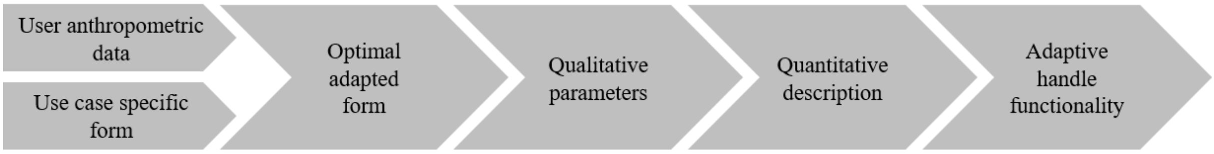

Figure 7. Design guideline for identifying design parameters for adaptive morphing handles

The use cases V1 to V4 were characterized by linear load transfers in X- and Z-direction. They show distinctive adapted forms and should therefore be used for further research and design parameter description. V5 to V7 can be classified as worst cases, since the load direction in the conducted experiment leads to a partial de-coupling between hand and handle as well as high pressure. These use cases are critical for adaptive handle design.

The handle's layout, relatively to the product it is attached to, is an adaptive handle's most basic parameter to vary. Translationally and rotationally moving the grip influences the posture of the hand-arm-system. This requires the superordinate product design to allow these degrees of freedom for the handle positioning. This is not always feasible, e.g. for a handle mounted to a bicycle handlebar. Due to the hand's complex anatomy however, the handle form can influence the hand-arm-system posture (Wang, 1999) in addition to the handle's layout. Handle length, base diameters, and convexity need to be derived from users' hands. These layout specific design parameters located on the handle directly are shown in Figure 8a. Additional layout parameters are the finger and thumb positions resulting from the hand's positioning relative to the handle. The support wing's positioning, extrusion, and are also layout parameters.

Form parameters describe the handle's design on a more detailed level, as shown in Figure 8b. The results described above indicate the importance of finger indentations' length, width, and depth in addition to their positions. Furthermore, the wing's thickness and the handles surface topology are an adaptive morphing handle's form parameters. These should follow the requirement to maximize contact surfaces for form closure primarily and for frictional coupling. Therefore, the qualitatively described design parameters serve as basis for future adaptive handle design iterations. They still require quantification.

Utilizing the presented experiment to analyse user specific and use case specific forms allows for such quantitative descriptions of the identified parameters. For this, further studies are proposed in chapter 6. Design guideline additions and requirements considering material are also recommended in the outlook.

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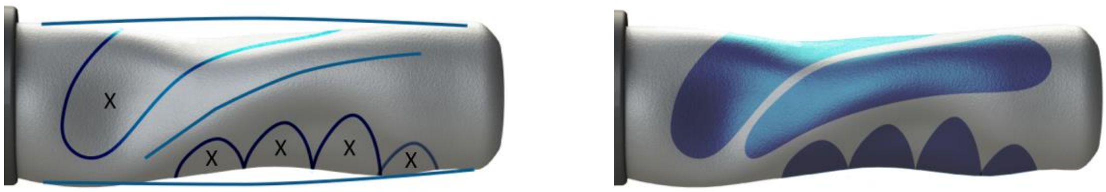

a) b)

Figure 8. Layout (a) and form (b) design parameters of adaptive morphing handles

6. Conclusion and outlook

To conclude, this work shows the suitability of the experiment design for identifying user specific and use case specific handle forms. The test stand and method also allow systematic evaluation of different handles considering user and use case. It is indicated that the adaptive handle in its current functionality leads to lower mean and peak pressure compared to a standardized and a personalized handle. While pressure between hand and handle can be compared systematically, results for hand-handle contact surface size have not been as clear. Since the pressure sensors are located right at the hand-handle contact surface, they interfere with haptic sensation and handle dimensions. Still, the experiment design should be applied to studies with larger subject samples, complemented with e.g. a subjective survey. To standardize grip force and identify interference with the load transfer, grip strength measurement using electromyography (EMG) can be integrated into the experimental setup. So, Lassmann et al.'s (2019) hypotheses concerning an adaptive handle's improved usability can be tested regarding load transfer efficiency.

Mechanical strength requirements of the adapted forms and the surface hardness need to be addressed in the future. The interference of sensors between hand and handle also have to be kept in mind when identifying design parameters for adaptive handle forms. Quantification of the identified parameters through the analysis of numerous user-use case combinations is to be done. Also, the parameters' influence on the load on users' hands and general usability should be analysed further. In this context acquisition and processing of subjects' anthropometric data, such as hand dimensions, wrist and arm angles, should also be further developed.

The parameters can then serve as requirements for new functional principles. This includes an integration of multi-material design and complex shape generation via generative algorithms for additive manufacturing as described by Watschke (2019).

So this work introduces a method for identifying user and use case specific form parameters and objectively examining handles' usability. It provides a basis for future research of the form morphing functionality for adaptive handles.

Acknowledgement

Funded by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation): Universal Design for adaptive handles for adjustment to specific operating scenarios - New effective principles enabled by additive manufacturing; project no.: 452009430

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