Comparison of subjective comfort ratings between anatomically shaped and cylindrical handles

Gregor Harih\textsuperscript{a}, Bojan Dolšak\textsuperscript{a}

\texttt{gregor.harih@um.si, bojan.dolsak@um.si}

\textsuperscript{a}Laboratory for intelligent CAD systems, Faculty of Mechanical Engineering, University of Maribor, Smetanova ulica 17, SI-2000 Maribor, Slovenia

Corresponding author: Gregor Harih, Tel.: +386 2 220 76 93, fax.: +386 2 220 79 94, e-mail: gregor.harih@um.si

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Abstract

Most authors have provided diameter recommendations for cylindrical handle design in order to increase performance, avoid discomfort, and reduce the risk of cumulative trauma disorders. None of the studies has investigated the importance of determining the correct handle shape on the subjective comfort ratings, which could further improve the handles' ergonomics. Therefore, new methods based on a virtual hand model in its optimal power grasp posture have been developed in order to obtain customised handles with best-fits for targetted subjects. Cylindrical and anatomically shaped handles were evaluated covering ten subjects by means of an extensive subjective comfort questionnaire. The results suggest large impact of the handle shape on the perceived subjective comfort ratings. Anatomically shaped handles were rated as being considerably more comfortable than cylindrical handles for almost all the subjective comfort predictors. They showed that handle shapes based on optimal power grasp postures can improve subjective comfort ratings, thus maximising performance. Future research should consider real conditions, since the comfort ratings can vary based on the specific task and by the tool selected for the task.

Keywords: tool handle, handle shape, comfort rating
1 Introduction
Ergonomic studies are wide-ranging, including the measurements, evaluations and analyses of workplaces, tools or even processes (Kaljun and Dolšak, 2012; Polajnar et al., 2012; Shuxing et al., 2008). Several authors have researched the topic of handle design in order to define the optimal size of a tool handle since a correctly designed handle can provide safety, comfort, and increased performance. Different authors have used different criteria for determining the optimal cylindrical handle: subjective comfort ratings (Hall and Bennett, 1956; Yakou et al., 1997); finger force measurements (Amis, 1987; Chen, 1991); muscle force minimisation (Sancho-Bru et al., 2003) and hand anthropometry (Blackwell et al., 1999; Garneau and Parkinson, 2011; Grant et al., 1992; Johnson, 1993; Oh and Radwin, 1993; Seo and Armstrong, 2008; Yakou et al., 1997). A few studies have also used two or more criteria: finger force measurements and muscle activity (Ayoub and Presti, 1971; Blackwell et al., 1999; Grant et al., 1992); subjective comfort ratings, finger force measurements and the electromyographic efficiency of muscle activity (Kong and Lowe, 2005). The broad variety of criteria used for determining optimal cylindrical handles has also dictated the uses of different methods. The recommended diameters of the cylindrical handles therefore vary from 25mm to 60mm, and above.

The mechanical behaviour of the skin and subcutaneous tissue is very important during grasping tasks as they are in direct contact and the forces and moments are transferred from the tool to the whole hand-arm system. Skin and subcutaneous tissue have non-linearly viscoelastic properties, where the skin is stiffer than the subcutaneous tissue (Wu et al., 2007). Both have low stiffness regions at small strains followed by a great increase in stiffness when increasing the strain. It has been shown, that higher contact pressures than those allowed for specific times can result in discomfort, pain, and ischemia. A power grasp produces very uneven distribution of forces and can yield to a contact pressure of the fingertip of 80kPa, which is excessive loading for skin and subcutaneous tissue (Gurram et al., 1995; Rossi et al., 2012). It has also been shown that foam materials can effectively reduce the contact pressure (Felkows and Freivalds, 1991). The finite element method has also been utilised for successfully modelling, comparing, and evaluating material choice during the design phase of a product (Novak, 2012).

In our previous research we thereby investigated and proposed hyper-elastic foam materials for a tool-handle based on the finite element method that took into account the non-linear behaviour of fingertips’ soft tissue, as they can lower the contact pressure whilst maintaining a low deformation rate of the tool-handle material for maintaining a sufficient rate of stability of the hand tool in the hands (Harih and Dolšak, 2013). Many powered hand tools also produce vibrations that are transferred from the handle to the hand. Deformations of skin and subcutaneous tissue whilst holding the tool and the vibration induced by the tool can lead to a disorder called “Hand-arm vibration syndrome” that may cause vascular, sensorineural and musculoskeletal disorders (Bernard et al., 1998; Youakim, 2009).

It has been also shown, that objects that follow the shape of the hand result in much lower local contact pressures of the soft tissue, which can prevent discomfort and several disorders (Wu and Dong 2005). However some authors have argued that a higher contact area can lower the subjective comfort ratings as a higher contact area triggers more pressure sensors in the soft tissue (Goonetilleke and Eng, 1994; Xiong et al., 2011). Therefore the designer has to find the optimal contact area that can increase the subjective comfort ratings, and attempt to lower the risk of hand-tool related musculoskeletal disorders. This study only evaluated the effects of increasing the contact area between the tool handle and the hand on the subjective ratings of discomfort, and did not attempt to evaluate how increasing the contact area affects injury risks.

Many researchers have paid a lot of attention to hand tools in terms of perceived discomfort. Comfort is strongly correlated to user performance and injury frequency (Kinchington et al., 2012; Kuijt-Evers et al., 2007; Mundermann et al., 2001). Subjective comfort is affected by physical, physiological, and psychological factors and is a subjectively defined feeling that differs from subject to subject (De
Looze et al., 2003). The uses of hand tools are mostly accompanied by feelings of discomfort that can be considered as a contradiction of comfort. Therefore designers have to optimise the size and shape of the handle in order to reduce the discomfort (Kuijt-Evers et al., 2004). The feeling of discomfort whilst using a hand tool can reduce the efficiency of the task and the user’s satisfaction (Fellows and Freivalds, 1991). A poorly designed tool handle can also cause cumulative trauma disorders of the hand and forearm if the task continues over a longer time period (Eksioglu, 2004).

Different predictors that have an influence on subjective discomfort-comfort rating while using a hand tool have been identified in previous papers (Kuijt-Evers et al., 2004). Based on a developed taxonomy, predictors can be combined into three factors: functionality, physical interaction and adverse effects on soft tissues, and lastly adverse effects on the skin (Kuijt-Evers et al., 2007). It has been shown that the functionality of a hand tool is one of the more important comfort and productivity predictors. The reduction of discomfort is mainly possible by optimisation of the functionality of the hand tool and the physical interaction between the hand and the handle. Kong et al., (2012) showed that increasing the required grip force also changes the subjective comfort rating from comfort to discomfort. The appearance of the hand tool does not make a direct contribution to the perceived discomfort but it can lead to user satisfaction whilst using the tool, and has a decisive impact on buying decisions. Therefore the designer also has to consider the aesthetics of the hand tool (Kaljun and Dolšak, 2012; Kuijt-Evers et al., 2004).

As comfort ratings when using hand tools are subjectively defined, it is also preferable to use subjective measurement methods such as hand tool testing of targetted populations and questionnaires, when evaluating a hand tool (Kuijt-Evers et al., 2007). Subjective methods have clear disadvantages such as time error and context effects (Annett, 2002). The time error effect can be attributed to the time between the presentation of the standard and the variable stimulus when the standard is held in memory and the context effects account for the multidimensionality of the ergonomics ratings. However objective methods (such as grip force and pressure measurements, electromyography, biomechanical hand models, finite element analyses, etc.) can only predict the physical aspects on the perceived comfort and do not directly correlate to the subjective comfort rating value (Kuijt-Evers et al., 2007).

Aldien et al., (2005) provided rough guidelines regarding pressure discomfort (PDT) and also pressure-pain threshold (PPT), where PPT is higher than PDT and the values differ according to the area of the hand. In addition different subjects have reported different values due to the subjective perception of the load on the hand. A PDT limit of 188kPa was reported by Aldien et al. (2005), however Fransson-Hall and Kilborn (1993) had estimated the value to be 104kPa. The wide-ranges of the PDT limits indicate that the connection of contact pressure on the perceived subjective comfort rating is still not clearly defined.

According to the finite-element simulations performed in by Wu and Dong (2005), it was shown that the surface curvature has a big influence on the resulting contact pressure on the fingertip when in contact with an object. Those objects that follow the shape of the hand and the skin’s surface result in much lower contact pressures and local deformations of the skin and subcutaneous tissue that can prevent discomfort and several disorders.

Previous studies have focused on cylindrical or elliptical shapes of the handles, and have provided mathematical models for diameter determination and design recommendations, as previously presented. None of them provided methods for determining the optimal shape of the handle in order to investigate its importance and also to improve the handle’s ergonomics. Nevertheless some authors have argued that the handles should vary in size between the hand and finger sizes, as the maximum voluntary finger contraction force is diameter-dependent (Kong and Lowe, 2005). In recent papers regarding this topic authors have also proposed, that further research into this topic should consider the shape of the hand during the optimal power grasp posture, in order to evaluate the importance of
the shape on perceived comfort and for optimising the shapes of the handles across different populations (Garneau and Parkinson, 2011).

The lack of correct handle shape determination and optimisation provides extensive room for the investigation and improvements in tool handle design. The aims of this study were to develop a mathematical method for customising tool handles to the shapes of particular users’ hands and to compare to the shape of the users' hands with handles that were cylindrical.

2 Mathematical approach for determining customised handles’ dimensions

2.1 Determination of an optimal cylindrical handle with variable diameters

According to developed hand grasp taxonomy, grasps can be divided into precision grasps and power grasps (Cutkosky, 1989; Napier, 1956). A heavy wrap power grasp was considered accordingly during this study as this kind of grasp is mostly used and best-suited for use with powered and non-powered hand tools, and provides maximal functionality, grip strength, and stability (Cutkosky, 1989).

Some previous studies have considered anthropometric data for obtaining an optimal handle diameter (Garneau and Parkinson, 2011; Kong and Lowe, 2005; Seo and Armstrong, 2008). Therefore the obtained mathematical models could also be used for determining the optimal handle diameter for a customised handle.

The equation for determining the optimal diameter of the handle with a single diameter from the study of Seo and Armstrong (2008) can be extended into equation (1) for a variable diameter of the handle regarding the index and middle fingers (Garneau and Parkinson, 2009).

\[
D_{opt|1,2} = \frac{D_{grip|1,2} \cdot \pi - \left(\frac{L_{F|1,2} + L_{F|T}}{2}\right)}{\pi}
\]

Eq. 1

Where :

- \(L_{F, 1, 2}\) = fingertip lengths of the index and middle fingers (Fig. 1)
- \(L_{F|T}\) = length of the thumb (Fig. 1)
- \(L_{1,2,3,4}\) = length of the hand from the wrist crease to the fingertip end for the index, middle, ring, and little fingers (Fig. 1)
- \(D_{grip|1,2}\) = inside grip breadth - diameter of the circle where the tips of the index or middle finger and thumb are in contact (Fig. 2 - left)
- \(D_{opt|1,2}\) = optimal diameter of the handle for the index and middle fingers (Fig. 2 - right)
Fig. 1: Anthropometric measurements needed for the calculations in equations (1), (2), and (3).

Fig. 2: Schematic drawing of the inside grip breadth $D_{\text{grip} | 1,2}$ (left) and optimal handle diameter $D_{\text{opt} | 1,2}$ (right).

It was assumed that the optimal handle diameter can also be obtained for the ring and little fingers with the relationship of the length of the index finger to the ring and little fingers – Equation 2.

$$D_{\text{opt} | 3,4} = \frac{L_{3,4}}{L_1} \cdot D_{\text{opt} | 1} \quad \text{Eq. 2}$$

In our study ten male subjects with no hand injuries or disorders and with a mean age of 21.6 (standard deviation 3.6) were used to obtain a custom-shaped handle for each subject. Participants were informed about the study and written consents were obtained. Afterwards anthropometric measurements of subjects’ hands were performed and were used in equations 1 and 2 in order to calculate the optimal diameters of the handles for each subject.

The obtained results were compared to the equation for optimal handle diameter obtained by Kong and Lowe (2005). They considered a constant handle and the optimal handle diameter handle could be obtained using the calculated NHS (normalised handle diameter) of 61.8% (equation 3).
De
spite the fact that their study only considered a constant diameter for the handle, it was obvious that the optimal handle diameter is calculated as the length from the wrist crease to the middle fingertip - $L_2$, as was also used in this paper. Therefore the control calculation of $D_{opt}$ can be directly compared to the optimal handle diameters $D_{opt|2}$ calculated in this study. The resulting diameters for cylindrical handles were almost equal despite the authors using different methods for diameter determination. Therefore it can be assumed that the resulting diameters have been verified.

3 Materials and Methods

3.1 Anatomically-shaped customised handle

As no methodologies exist for the development and manufacturing of anatomically-shaped customised handles, a standardised methodology was developed for obtaining anatomically-shaped customised handles and for evaluating and comparing them with cylindrical handles.

3.1.1 Optimal cylindrical handle with variable diameters

The calculated diameters in the previous section were used for manufacturing customised cylindrical pre-handles with variable diameters out of hard polyurethane, for each subject. Anthropometric measurements were performed on each subject in order to obtain the sectional size according to each finger width. Manufactured optimal cylindrical handles with variable diameters were tested with by the corresponding subjects and it was shown that the calculated diameters were correct, as there was an overlapping of the tip of thumb with the fingertips of index and middle fingers, as calculated (Fig. 3).

![Fig. 3: Testing the optimal cylindrical handle with variable diameters.](image)

3.1.2 Optimal power grasp posture fixation during shape acquisition

An outer hand mould was manufactured whilst softly holding the optimal cylindrical handle with variable diameters in order to maintain the diameters and the shape of the power grasp posture with non-deformed skin and subcutaneous tissue. The outer hand moulds were manufactured by two Physiotherapists at The Institute of Physical and Rehabilitation Medicine, University Medical Centre Maribor. Orthotic material Orflight® (Orfit Industries, Belgium) was used with a thickness of 2.5mm and micro perforation that had great ability for moulding to anatomical contours. A rough shape of the extended subject’s hand was cut-out of a 45x60cm plate. The cut-out shape was activated in a hot
water bath with an ideal activation temperature of 65°C. The mould was shaped on the dorsal side of the subject’s hand when softly holding the optimal cylindrical handle with variable diameters. The hand was in a neutral position according to ergonomic recommendations. The basic shape of the mould was accomplished within the activation time. After the hardening, smaller corrections were made with a hot air gun. After the shape of the mould was declared as satisfactory, straps were added for the hand and hand-opening fixations (Fig. 4).

![Image](image.jpg)

**Fig. 4:** View from above of the outer hand mould attached to the hand.

### 3.1.3 Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) was performed at the Radiological Department of the University Medical Centre Maribor. The MRI machine was a GE medical systems Signa HDxt 3.0T. The subjects scanning position was HFDR (Head First-Decubitus Right) with the extended hand (Fig. 5). The used coil was a one channel HD Knee/Foot Coil that allowed the best positioning of the hand during the scanning. Before the scanning, an optimal cylindrical handle with variable diameters was used to finely adjust to the correct size of the outer hand mould for each subject. The optimal cylindrical handle with variable diameters was removed during the scanning in order to obtain the shape of the non-deformed skin and subcutaneous tissue. The outer mould and the hand were fixed with foam, which prevented any movement of the hand during scanning (Fig. 5). The slice thickness was set at 1mm to avoid unnecessarily small anatomical structures and surface details. The scanning time was about fifteen minutes. Every subject was told to hold his/her hand in an open position touching the mould during the scanning in order to maintain the proper diameters and shape of an optimal power grasp. The scanned images were provided in the DICOM format.

![Image](image.jpg)

**Fig. 5:** MR imaging of the subjects’ hands with outer hand moulds attached.
3.1.4 Segmentation and 3D reconstruction
A professional medical imaging and editing software Amira® 5.3.3 (Visage Imaging) was used for the segmentation and 3D reconstructions of the DICOM images. Segmentation was performed using a threshold technique as only the surface of the hand was needed and no differentiation in anatomical structure of the hand was necessary. Preliminary 3D reconstructions showed that the model was anatomically accurate and the produced outer surface highly detailed. In order to obtain a smoother surface a “resample” module was added to the segmentation and the 3D reconstruction process. The result was a smooth 3D representation of the subject’s hand in power grasp posture (Fig. 6).

![Fig. 6: Obtained 3D hand in Amira® in optimal power grasp posture.](image)

3.1.5 Anatomically-shaped customised tool handle
The .STL file for each subject obtained in Amira® software was imported into commercial CAD software CATIA® V5R20. A mathematically defined surface model was generated within a Surface reconstruction module. The surface model was then converted into a mathematically-defined volumetric model using a Close Surface tool in in the Part Design module. An elliptical cylinder was modelled in order to obtain the customised shaped handle for power grasp posture. The size and the position of the cylinder were determined so that the cylinder fully overlapped the palmar empty volume created by the hand during the optimal power grasp posture (Fig. 7).

![Fig. 7: 3D hand and elliptical cylinder in an overlapping position.](image)
In order to obtain the customised handle, the Boolean operation “Remove” was used that removed the cylinder model volume, which was in overlap with the hand model volume. Despite resampling during the 3D reconstruction, the resulting handle was full of small surface details that were the result of the surface details of the scanned hand. These anatomical details were so small that their contribution to handle comfort and contact area was assumed to be negligible. Therefore it was, from in regard to manufacturing and aesthetic considerations, reasonable to add additional smoothing to the 3D reconstructed hand in order to obtain a smoother and aesthetically more appealing handle. Additionally the sharp edges were rounded to avoid any chances of injury (Fig. 8).

![Anatomically-shaped customised handle](image)

**Fig. 8:** Anatomically-shaped customised handle.

In order to compare and evaluate the anatomically-shaped customised handle with the cylindrical handle, the customised handles were manufactured using a rapid prototyping technique.

### 3.2 Subjective comfort ratings

#### 3.2.1 Subjects and task description

The subjects were each provided with an informed consent form and a description of the measurements procedure. They were told to stand comfortably with their elbows at ninety degrees and wrists in neutral positions. They were asked to perform the task of gripping the handle with their preferred normal grip force whilst applying a push force of 50N on the handle, which was mounted onto a force gauge. In this way standardised and more generalised simulations of a common task were performed using hand tools. This was assumed as most tasks that require power or pistol grip produce normal forces on the hand’s surface. The same task was also performed by each subject with a corresponding cylindrical handle. The utilised general task provided exactly the same task for each subject. Based on this generalised task each subject corresponded to his/her distinctive physiological response and subjective rating of the handle, and was therefore task independent. The major limitation of the generalised task was its generality, which did not consider the use of the handle on real tools and real tasks.

#### 3.2.2 Subjective ratings questionnaire and data acquisition

In order to compare and evaluate the newly-developed and manufactured customised shaped handles and the circular handles, a questionnaire was adapted containing a variety of questions relating to handle comfort and performance, based on the paper of Kuijt-Evers et al. (2007) (Table 1). The
subjects rated the handle comfort descriptors on a scale containing 7 discrete levels (from 1 = totally disagree to 7 = totally agree) (Kuijt-Evers et al., 2007).

Table 1 - Subjective comfort ratings questionnaire.

<table>
<thead>
<tr>
<th></th>
<th>Totally disagree</th>
<th>-</th>
<th>Disagree somewhat</th>
<th>-</th>
<th>Agree somewhat</th>
<th>-</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fits the hand</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Is functional</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Is easy in use</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Has a good force transmission</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Has a nice-feeling</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Can offer a high task performance</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Provides a high product quality</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Looks professional</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Needs low hand grip force supply</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Has a good friction between the handle and hand</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes an inflamed skin of hand</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes peak pressure on the hand</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes blisters</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Feels clammy</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes numbness and lack of tactile feeling</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes cramped muscles</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

In order to evaluate the different areas of the handle, we extended the subjective comfort rating questionnaire to include comfort – discomfort predictors for six distinctive anatomical areas of the hand: the thumb, the index, middle, ring and little fingers, and the palm, in order to evaluate the subjective comfort ratings (Table 2).

Table 2 - Subjective comfort rating questionnaire for six distinctive anatomical areas of the hand.

<table>
<thead>
<tr>
<th></th>
<th>Totally disagree</th>
<th>-</th>
<th>Disagree somewhat</th>
<th>-</th>
<th>Agree somewhat</th>
<th>-</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fits the area</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Provides a nice-feeling</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes an inflamed skin of hand</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes peak pressure on the hand</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes blisters</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes numbness and lack of tactile feeling</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Causes cramped muscles</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

The overall subjective comfort ratings were evaluated by the subjects (Table 3).

Table 3 - Overall subjective comfort ratings questionnaire.

<table>
<thead>
<tr>
<th>Overall comfort:</th>
<th>Very uncomfortable</th>
<th>-</th>
<th>A little uncomfortable</th>
<th>-</th>
<th>A little comfortable</th>
<th>-</th>
<th>Very comfortable</th>
</tr>
</thead>
<tbody>
<tr>
<td>I think this handle is:</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>
After the data had been collated it was edited and the mean values of the standard deviations were calculated in order to evaluate and discuss the results.

4 Results

4.1 Method verification and the objective measurements

Additional objective measurements were also considered for verifying the proposed methods of obtaining the customised shaped handle and for evaluating and comparing both handles.

Virtual measurements on the obtained customised shaped handles in CATIA® showed that the optimal diameters for each handle were withheld by the outer hand mould during the MRI within small deviations, therefore it could be assumed that the subject’s hand was in its optimal power grasp posture.

In order to compare the contact area between the customised shaped handles obtained during this study and the corresponding cylindrical handles of optimal diameters, the cylindrical handles corresponding to each subject were manufactured using hard plastics. The diameters of the cylindrical handles were determined based on anthropometric measurements and according to equation 1. The measured mean contact area of the customised handles was, on average, over 25% higher than for the optimal cylindrical handles.

4.2 Overall handle subjective comfort predictors rating

Firstly, the overall handle subjective comfort predictor rating questionnaire was evaluated (Fig. 9). In order to determine whether there were statistically significant differences between both handles, we utilised a dependent samples T-test. The results also showed high values for standard deviations. This was expected as perceived subjective comfort is subject-dependent and therefore can vary from subject to subject.

Comfort descriptors ‘Fits the hand’, ‘Is easy in use’ and ‘Offers a nice grip feeling’ were statistically significant different at p<.05 and were rated higher for the customised shaped handle than for the cylindrical handle. The ‘Has a good force and moment transmission’, ‘Is a high quality handle’, ‘Offers a high task performance’, ‘It provides high quality of the total product’, ‘Looks professional’, ‘Needs low hand grip force supply for stable grip’ and ‘Has good friction between handle and hand’ comfort predictors were were statistically significant different at p<.01 and were rated higher for the customised shaped handles. The results showed that other comfort predictors were statistically not different.
The influence of the handle shape on the overall subjective comfort ratings was additionally compared when evaluating the comfort predictors for both handles regarding the distinctive areas of the thumb, the index, middle, ring and little fingers, and the palm.

The results showed that only one comfort predictor (‘Causes blisters in the area’) was statistically different at p<.05 (Fig. 10).

![Diagram of comfort predictors](image-url)
For the anatomical area of the thumb, the results showed statistically significant difference at $p<.05$ for the comfort predictors ‘Causes peak pressures on the area’, ‘Causes blisters in the area’ and ‘Causes numbness and lack of tactile feeling in the area’ (Fig. 10).

For the anatomical area of the index finger, the results showed statistically significant difference at $p<.05$ for the comfort predictors ‘Causes peak pressures on the area’, ‘Causes blisters in the area’ and ‘Causes numbness and lack of tactile feeling in the area’ (Fig. 11).

The anatomical area of the middle finger showed that there were statistically significant differences at $p<.05$ in the comfort predictors ‘Area offers nice grip feeling’, ‘Causes inflamed skin on the area’ and ‘Causes cramped muscles in the area’. There were statistically significant differences at $<.01$ for the comfort predictors ‘Causes peak pressures on the area’. Amongst all the statistically different comfort predictors, the customised handle was rated better than the cylindrical handle (Fig. 12).
The measured anatomical area of the ring finger showed statistically significant differences at p<.05 in comfort predictors ‘Anatomical part fits the area’, ‘Causes an inflamed skin on the area’, Causes blisters in the area’, ‘Causes numbness and lack of tactile feeling on the area’, and statistically significant differences at p<.01 for comfort predictors ‘Area offers nice grip feeling’, ‘Causes peak pressures on the area’ and ‘Causes cramped muscles in the area’ (Fig. 13). All the comfort predictors were rated better for the customised handle.

For the anatomical area of the little finger, the results showed statistically significant differences at p<.05 for all the measured comfort predictors (Fig 14.).
The final measured anatomical area was the hand palm. The results showed statistically significant differences at $p<.01$ for comfort predictors ‘Causes an inflamed skin on the area’ and ‘Causes blisters in the area’. All other comfort predictors were statistically significant different at $p<.05$.

4.4 Overall handle subjective comfort ratings

Finally the overall comfort was evaluated. The results from the questionnaire showed statistically significant difference between both handles at $p<.01$. The customised handle was rated at 5.2 and the cylindrical handle was 3.4 (Fig. 16.).
5 Discussion

5.1 Method verification and objective measurements
As the optimal diameters for each finger were withheld by the customised tool-handle, the voluntary contraction force was thereby maximised, which increased the user performance whilst using the tool with the customised handle (Seo and Armstrong, 2008). The subjective comfort ratings, which were based on the subjects’ preferences regarding grip diameter sizes, were also increased, as there are small deviations according to the study from Kong and Lowe (2005).

The increase in the contact area was expected as the optimal shaped handle follows the anatomical shape of the hand in its optimal power grasp posture. Therefore the contact area is also maximised. According to Seo and Armstrong (2008) the greatest contact area in their study was obtained with diameters of 51mm and 58mm for cylindrical handles, which contradicts the optimal diameters for maximizing the voluntary contraction force and subjective comfort maximisation, thus suggesting smaller diameters. Therefore it is obvious that contact area maximisation is impossible with cylindrical handles when considering the optimal diameter for maximising voluntary contraction and comfort ratings. Therefore, it has been shown that contact area maximisation is only possible when considering the anatomical shape of the hand in its optimal power grasp posture. Having the anatomical shape of the handle and also therefore greater contact area, high overall and local contact pressure can be avoided. Thus the shape of the handle obtained in this study is more likely to prevent cumulative trauma disorders that are pressure induced and can provide greater comfort ratings than a cylindrical handle. In order to prove this, the results from the extensive subjective comfort ratings questionnaire are evaluated and discussed in following sub-sections.

5.2 Overall handle subjective comfort predictor ratings
Based on the obtained results from the subjective comfort ratings questionnaire we firstly discuss the overall handle subjective comfort predictors rating and compare both handles.

Higher ratings for the comfort descriptors ‘Fits the hand’ and ‘Offers a nice grip feeling’ of the customised handle can be explained by its anatomical shape, because it considers the optimal power grasp posture and thereby provides best-fit for the targeted subject. As the functionality of the handle adds to the whole product’s functionality, it is also one of the more important comfort predictors. This is evident with good correspondence when comparing the ‘Is functional’ comfort predictor with the ‘Overall comfort’ of the handle: the functionality of the cylindrical handle was rated at 3.7, whilst the customised handle was rated at 5.4 and the overall comfort of the cylindrical handle at 3.4, whilst the customised handle was rated at 5.2. The comfort predictor ‘Is easy in use’ is statistically significant different between both handles despite a lower value being expected for the anatomically-shaped handle, as it provides only one feasible grasp position, whilst the cylindrical provides several due to its axle symmetry.

In order to provide stability whilst holding the cylindrical handle, the exerted normal finger force has to be reasonably high to prevent slippage and rotation in the direction of the handle axis. With high exerted normal forces, high local and overall contact pressures occur, which can cause discomfort and also task-related disorders (i.e. blisters, inflamed skin, cramped muscles…). Therefore handle slippage and rotation should be prevented by an appropriate shape of the handle. When using the customised handle obtained in this study, the stability of the tool is greatly increased as the majority of the forces and moments are transferred over the anatomical handle shape and much less by the friction between the handle and the hand. Therefore a lower normal grip force can be exerted in comparison with the cylindrical handle and the tool can be held stable in the hand.

This is clearly evident from the comfort predictors ‘Has a good force and moment transmission’ and ‘Needs a low grip force for stable grip’, which were rated better for the customised shaped tool-handles. In the comfort predictor ‘Has a good friction between handle and hand’ it is evident that the subjects referred to friction that is caused by the forms of the handles and not the material friction
between the hand and the handle. In order to measure the material friction, the questionnaire should be appropriately revised. Subjective comfort ratings that describe the handle quality (‘Is a high quality handle’, ‘It provides high quality to the whole product’) and visually (‘Looks professional’) were rated better for the customised handle. This can be explained by past user experiences and expectations as hand tools, and therefore also handles with good fit to the user, have higher functionality and also performance.

The comfort predictor ‘Offers a high task performance’ is based only on user expectations as the generalised task did not consider the measurements of productivity. More precise results could be obtained with the usages of both handles on actual hand tools, although the generality would be thereby lost. As locally badly-designed handles that affect only one anatomical area can cause a lower value for the overall comfort rating, it can be assumed that this would be the case for the comfort predictors ‘Causes an inflamed skin of the hand’ and ‘Causes peak pressures on the hand’. Based on the overall handle subjective comfort predictors, by using the questionnaire it is impossible to determine whether the whole handle causes the higher contact pressure or just one anatomical part. Therefore the results from handle subjective comfort predictor ratings for distinctive anatomical areas are evaluated in next sub-section. It can be assumed that the same effect could be attributed to the result from the comfort predictors ‘Causes blisters’ as both comfort predictors are usually correlated.

The comfort predictors ‘Feels clammy’ in this study can be considered as a control question for verifying whether the subjects took the measurements and questionnaires seriously as both handles were made out of the same material with almost the same surface finish. The results show that the subjects rated both handles with exactly the same rating and the T-test revealed there was no statistically significant difference between both handles. It can therefore be assumed that the subjects took the measurements and questionnaires seriously and the results represent their subjective comfort ratings.

No significant differences were observed for the comfort predictors ‘Causes numbness and lack of tactile feeling’ and ‘Causes cramped muscles’. This can be attributed to the same effect of badly designed anatomical areas of the handle. The cause of numbness and lack of tactile feeling usually occurs when high contact pressure on a nerve is present or high contact pressure prevents the blood flow in the underlying soft tissue, which can cause ischemia.

5.3 Handle subjective comfort predictors ratings for distinctive anatomical areas

The results show that the thumb was the area that caused lower comfort ratings for the customised handle for the comfort predictors ‘Causes an inflamed skin’ and ‘Causes peak pressures on the hand’, as all these comfort predictors are statistically not significant different between both handles. Visual inspection of the handle showed that the higher ratings were due to the deep thumb grooves on the customised handles (Fig. 17). When applying higher grip force, the relative position of the thumb changes slightly that causes rubbing of the skin and higher local contact pressures within that area. The same effect was reported by the test subjects whilst interviewing them after performing the measurements. In this study the used handle material was hard plastic, which additionally revealed the design flaws of the handles and therefore higher impact on the perceived subjective comfort ratings. Therefore the actual tool handle should have a softer cover material such as rubber to avoid high local contact pressures and thereby provide increased subjective comfort ratings. Therefore this area should be redesigned in the form of a smaller groove for improving the comfort predictor rating for the anatomically-shaped customised handle. Therefore more accurate results on the influence of the handle shape on the overall handle comfort could also be obtained in the future.
The advantage of correct handle shape determination can be seen from the subjective comfort predictors for all the distinctive anatomical areas when evaluating and comparing both handles. In regard to the cylindrical handle the diameter is determined and therefore also optimised based only on the length of one finger. This is usually the index or the middle finger that make the greater contribution to the subject’s maximum voluntary contraction force. Therefore the cylindrical handle design does not allow diameter optimisation for all the fingers. This is only possible with correct handle shape as the diameters for each finger are optimised based on the optimal power grasp posture.

For the index finger both handles have almost the same subjective comfort predictors ratings for ‘Anatomical part fits the area’ and ‘Area offers nice grip feeling’ and are statistically not significant different (Fig. 11). This was expected as the diameter of the cylindrical handle is the same as the diameter of the customised shaped handle and therefore provides almost the same grip quality. The deviation from the optimal diameter for the middle finger regarding the cylindrical handle can be seen from the lower subjective comfort ratings for both comfort predictors (Fig. 12). The deviation is even higher for the ring and little fingers and thereby also the corresponding two subjective comfort predictors respectively (Figs 13 and 14).

The customised handle subjective comfort predictors ‘Anatomical part fits the area’ and ‘Area offers nice grip feeling’ have almost the same ratings for all the fingers, which indicate that the grip quality is the same for all the fingers. This can be attributed to the anatomical shape determination of the customised handle. However both comfort predictors did not exceed a comfort rating of 5.7 on the scale. Based on previous research this effect can be most likely explained by the psychological effects of user experiences and expectations. Most of the subjects namely thought that from past experiences there are still improvement potentials possible for tool handles and reflected this in their subjective comfort ratings, as using a tool handle is mostly accompanied by feelings of discomfort.

Other subjective comfort ratings predictors which were negative correlated with the perceived comfort (‘Causes an inflamed skin on the area’, ‘Causes peak pressures on the area’, ‘Causes blisters in the area’, ‘Causes numbness and lack of tactile feeling on the area’, ‘Causes cramped muscles on the area’) are consistent and considerably lower rated for the customised shaped tool handle. This can be explained by the anatomical shape of the customised handle that provides the best fit to the subject.

The middle finger has, according to previous research, the second largest impact on the overall perceived comfort after the palm, therefore it is necessary to pay special attention to this area in order to increase the overall perceived comfort. Based on the results, the anatomically-shaped customised handle provided higher ratings of subjective comfort predictors (Fig. 12).
The ring and little fingers provide a lower contribution to the total maximum voluntary contraction respectively. Therefore many authors do not pay attention to the correct diameter and shape when determining these areas. However, the results show that with an anatomical shape for each corresponding area, the subjective comfort ratings can be increased (Figs 13 and 14). Those anatomical shaped areas and optimal diameters that maximise voluntary contraction also increase the stability of the handle in the hand. Every subjective comfort rating’s predictor is statistically significant different between both handles for the ring and little fingers.

It has been previously shown that the greatest impact on the overall perceived subjective comfort has the anatomical area of the palm. The customised handle was rated better for all the subjective comfort predictors that were statistically significant different between both handles (Fig. 15). The ratings for the subjective comfort predictors ‘Anatomical part fits the area’ and ‘Area offers nice grip feeling’ were almost the same as for the ratings of the fingers. Therefore it can be assumed that the anatomically-shaped customised handle provides almost the same grip quality for the palm as with the fingers. All other subjective comfort predictors that were negatively correlated with the overall comfort were considerably lower for the customised handle compared to the cylindrical handle.

5.4 Overall handle subjective comfort ratings
Based on the results of the overall handle subjective comfort predictor ratings and the Handle subjective comfort predictor ratings of distinctive anatomical areas it was expected that the customised handle would be rated as more comfortable than the cylindrical handle. The customised handle was rated 5.2, whilst the cylindrical handle was rated 3.4. Therefore the anatomically-shaped customised handle can be considered as more comfortable in comparison with the cylindrical handle. An improved design of the thumb groove of the customised shaped handle could additionally improve the subjective comfort predictors in comparison with the cylindrical handle, which could lead to higher overall handle subjective comfort ratings of the anatomically-shaped customised handle.

The limitation of this study was the relatively small sample size; nevertheless the t-tests showed statistical significances at p-values of .05 or even .01. More accurate results could also be obtained with larger subject samples. Another limitation was also the generalised measurements procedure that did not consider the use of the handle on real tools and tasks. Future research should consider real conditions, as the comfort rating can vary based on the specific task, which is dictated based on the used hand tool. Besides the optimal cylindrical handles, other more common shapes of the handles could be considered during the evaluation and analyses. Based on the desired task and hand tool, recommendations regarding the shape of the handle could be investigated and provided to the designers. A symmetrical and topologically generalised handle could be developed based on the customised handle for use over a broader variety of tasks and also targetted populations. Although user comfort is mostly evaluated using subjective questionnaires, objective measurements (e.g. muscle activity, contact pressure mapping, finger grip force distribution, maximum grip force, hand-wrist postures) could be performed and analysed in the future, as they could provide the physiological effects and predict the comfort rating and initiators of cumulative trauma disorders. Therefore, the relationship between the subjective comfort ratings and the objective measurements could be compared and assessed.

6 Conclusion
The optimal power grasp posture of the anatomically-shaped customised handle provides optimal diameters for each finger where the maximum voluntary contraction can be achieved. This is impossible when using the cylindrical handle as it takes into account only one finger during the optimal diameter determination. It has been shown that the shape of the handle has significant impact on the subjective comfort ratings as the anatomically-shaped customised tool handles were rated considerably higher than the cylindrical handles. The ratings of subjective comfort predictors showed that the customised handles were better rated for functionality, which is one of the more important
comfort predictors. Anatomically-shaped handles were also better rated for subjective comfort predictors ‘Fits the hand/area’ and predictors regarding stability, quality and visual appearance. Based on the subjective comfort predictor ratings for the distinctive anatomical areas it was shown that the customised handles that consider the optimal power grasp posture provided high comfort rating and therefore high grip quality for all distinctive anatomical areas. With the cylindrical handle optimisation for all distinctive anatomical areas is impossible due to the cylindrical handle being optimised for only one optimal diameter. The anatomically-shaped custom handles that provide the best fits for targetted subjects can improve their subjective comfort ratings but however over-differentiated shaped handles can cause discomfort. The results also showed that a badly-shaped handle area can have great impact on the overall comfort rating of the handle. Therefore correct handle shape determination can improve subjective comfort ratings for a targetted subject, which can increase user performance and lower the chances for fatigue or injuries. The aim of this research was to investigate the importance of correct handle shape determination, which can improve the handle’s ergonomics and therefore create added-value to the product and increase the value and competitiveness of the product on the market. Therefore researchers should also pay attention, beside the handle diameter optimisation, to correct handle shape determination in order to improve handle ergonomics. This study provides a base for further research, which could investigate the optimal shape determination of the handle for broader targetted populations.

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