Tool-Handle Design Based on a Digital Human Hand Model

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Abstract

A significant part of manual work is still done using hand-tools. Therefore, a correct design is crucial for preventing upper-extremity musculoskeletal disorders, such as carpal tunnel syndrome, hand-arm vibration syndrome, tendinitis, etc. When considering the ergonomics of a hand-tool, in addition to its main functionality, the most important part is the tool’s handle. Most of the authors have considered cylindrical handles and provided guidelines and mathematical models for determining optimal diameters in order to maximise finger-force exertion, comfort, contact area, thus minimising the chances of cumulative trauma disorders (CTD). However, they have not taken into account the shape of the hand during optimal power-grasp posture when determining the tool-handles’ shapes, which could additionally improve the handles’ ergonomics. In order to overcome this limitation, we have developed an anatomically accurate static digital human-hand model (DHHM). The developed DHHM allows direct tool-handle modelling and does not require an iterative design process when designing a tool-handle with improved ergonomics. In order to develop DHHM, anthropometric measurements on ten subjects were performed for the manufacturing of corresponding optimal cylindrical pre-handles with variable diameters for each finger. Outer hand moulds were manufactured based on the pre-handles for obtaining the shape of the hand with skin and subcutaneous tissue undeformed. Magnetic resonance imaging was conducted with the outer hand moulds attached, and segmentation and 3D reconstruction were performed on the images to obtain the DHHMs for each subject. Tool-handles based on DHHM were then obtained within common Computer-Aided Design software. Measurements on the handles based on the DHHM have shown that they provide: on average, an over 25% higher contact area compared to the corresponding cylindrical handle. With higher contact area and anatomical shape of the handle, extensive deformation of the soft tissue can be avoided, thus preventing excessive load on the hand. Subjects also compared these DHHM handles with cylindrical handles regarding perceived subjective comfort-rating. It was shown that those tool handles based on the DHHM provided a higher overall comfort-rating compared to cylindrical handles. It has also been demonstrated that anatomically shaped tool-handles based on the developed DHHM can improve user performance and lower the risk of CTD.

Relevance to industry: This paper introduces methods for developing a static DHHM for an optimal power-grasp posture by directly modelling a tool-handle with improved ergonomics. It also demonstrates also that anatomically-shaped tool-handles based on the developed DHHM with optimal power-grasp posture increases the contact area and the subjective comfort-rating, thus increasing user performance and lowering the risk of CTD.

Keywords: product development, ergonomics, tool-handle design, handle’s shape, digital human hand-model, 3D hand model

1 Introduction

Ergonomic principles should be included in the phase of industrial/mechanical product design before the engineers tackle the problem, because the main function of the product and the form of the product are usually strongly connected (Hogberg et al. 2008, Shuxing et al. 2008). The whole human-product system performance is also human-dependent, therefore a designer has to consider the ergonomics in order to achieve the expected system efficiency and prevent cumulative trauma disorders (CTD) of the users (Hogberg et al. 2008).

A significant part of manual work is still done with hand-tools, despite the automation in many industries. Badly-designed hand-tools can induce upper-extremity musculoskeletal disorders; such as carpal tunnel syndrome, hand-arm vibration syndrome (HAVS), tendinitis, etc. These CTDs account for about one third of the sick leaves of workers, resulting in high workers’ compensations claims (Punnett and Wegman 2004).
The broad variety of powered and non-powered hand-tools has steered that many authors; when researching the topic of tool-handle design; into defining the optimal sizes and shapes of tool-handles. A correctly-designed handle can provide safety, comfort and increased performance (Eksioglu 2004). Most authors have focused on the cylindrical or elliptical shapes of the handles, but none of them have considered the anatomical shape of the hand when in the optimal power-grasp posture during the designing of tool-handles. It has been shown that the maximum voluntary finger contraction force is diameter-dependent, therefore handles should vary in size according to hand and finger sizes (Kong and Lowe 2005). Therefore the authors Garneau and Parkinson (2011) suggested that any further research into this topic should consider the shape of the hand at its optimal power-grasp posture in order to obtain maximum grip-force, with lowest stresses on ligaments, tendons, and soft tissue, thus lowering the risk of CTDs (Khalil 1973).

The mechanical behaviour of the skin and subcutaneous tissue is crucial during gripping tasks, since forces and moments are transferred from the tool to the whole hand-arm system. Skin and subcutaneous tissue have non-linear viscoelastic properties, where the skin is stiffer than the subcutaneous tissue (Wu et al. 2007). Both have low stiffness region at small strains; followed by a greater increase in stiffness when increasing the strain. A power-grasp can also yield a contact pressure on the fingertip of 80kPa, which creates excessive loading for the skin and subcutaneous tissue (Gurram et al. 1995). It has been shown, that any higher contact pressures than allowed for over a specific time can result in discomfort, pain, and ischemia. Excessive loading can also result also in other CTDs; such as carpal tunnel syndrome (Eksioglu 2004). Hand-handle contact-force and therefore the contact pressure; as well as the grip and push-forces, are also handle diameter dependant (Welcome et al. 2004). The smallest investigated cylindrical handle (30mm) has shown to yield in highest magnitude of contact-force, which also suggests highest contact pressure. Aldien et al. (2005) have shown that the higher grip and push-forces on a cylindrical handle can produce concentrated contact-forces and pressures that exceed the limit of pressure discomfort (PDT) and sustained pressure (SP) values for preserving work efficiency over a working day. Therefore authors have already suggested that further research should identify a handle size and shape that distributes the contact-forces and pressures more evenly with PDT and SP within acceptable values. Many of powered hand-tools produce vibrations, which are transferred from the handle to the hand. Deformations of skin and subcutaneous tissue whilst holding the tool; plus the vibration induced by the tool; can lead to HAVS that may cause vascular, sensorineural and musculoskeletal disorders (Bernard et al. 1998, Youakim 2009).

This extensive ergonomic knowledge that is necessary during the design phase of a tool-handle; and its poor integration with existing, well-established CAD software, has affected companies that do not or on very low scales address ergonomic principles during the design phase (Kaljun and Dolšak 2012). In order to overcome this issue, several digital-human models (DHM) have been developed over recent decades. Within DHMs, the human is represented digitally inside a virtual environment, where analyses can be performed without physical prototypes (Demirel and Duffy 2007a, Demirel and Duffy 2007b). Based on these analyses, safety and performance can be predicted and design errors can be identified and corrected during the design phase.

Usually those hand-arms of Digital Human Models that are parts of a whole digital body models are used to evaluate the vision and clearance. Nowadays DHMs based on kinematics and biomechanics are also used for evaluation of tasks; such as lifting or pushing (Chaffin and Andersson 1999). However; most of the DHMs do not incorporate anthropometric and anatomically-correct human hands, thus preventing ergonomic analyses; and product and tool development where the grip is the main ergonomic design attribute. The level of accuracy regarding the ergonomic analyses of hand-grip based on DHM relies on the model's level of accuracy. Therefore those hands of DHM that only consider the kinematics and biomechanics of the hand, but neglect the anatomical shape of the hand and soft tissue deformation whilst gripping, cannot be used for realistic ergonomic analyses; and product shape determination and optimisation (Nierop et al. 2007).
In order to overcome this issue, a few authors have recently developed stand-alone anatomically-accurate Digital Human Hand Models (DHHMs) for ergonomic evaluation of hand-held products. They are mostly anthropometric models that are modelled based on magnetic resonance imaging (MRI) or computed tomography (CT) that utilise mathematical models to predict a viable human grasp for a target product (Endo et al. 2007, Peña-Pitarach et al. 2009). However the complexity behind the phenomena of grasping can also lead to non-viable grasping of the product by the mathematical models.

These DHHMs are designed for ergonomic analyses of existing virtual 3D models of products, therefore designers still have to possess comprehensive knowledge of ergonomics in order to lower the design iterations and to obtain a product containing the desired ergonomics. DHHMs do not allow for direct development of the product’s shape and size that is within their interactions with the humans.

Grasps generated by the mathematical model are usually evaluated by the operator visually or by calculating grasp quality using different methods within the software. This kind of evaluation can be unreliable, since real-world grasping is very complex and is also dependents on the subjective comfort rating of the user (De Looze et al. 2003). It has been shown that perceived subjective comfort is strongly correlated with user performance, therefore it is necessary to incorporate this aspect of product evaluation during the design phase (Kuijt-Evers et al. 2007). Comfort is affected by physical, physiological, and psychological factors; and is a subjectively-defined feeling that differs from person to person. Therefore it cannot be simply predicted neither by objective methods (such as grip-force and pressure measurement, electromyography, biomechanical hand-models, finite element analyses, etc.) nor by the resulting mathematical models that can only predict the physical aspects on the perceived comfort (De Looze et al. 2003). Thus using subjective measurement methods is preferred when evaluating a handle. The usages 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 the shape of the handle in order to reduce the discomfort (Kuijt-Evers et al. 2004).

Therefore the aim of this paper was to overcome those limitations of current DHHMs regarding the tool-handle design that require extensive ergonomic knowledge and iterative design process. Thus we propose methods for developing a static DHM in its optimal power-grasp posture for directly modelling a corresponding tool-handle with improved ergonomics. The objective was to evaluate whether the developed DHM based on optimal power-grasp posture can lower the risk of CTD whilst increasing the subjective comfort-rating. Therefore our approach also includes user-testing and thereby real-world verification and validation of the proposed methods and the resulting tool-handle; that would allow for the future optimisation of the tool-handles’ sizes and shapes; in order to define optimised handles for a wider population with lower risks of CTD and higher subjective comfort-ratings.

2 Methods

2.1 Determination of the optimal cylindrical pre-handle

Different authors have used different criteria for determining the optimal cylindrical handle: subjective comfort-rating (Yakou et al. 1997, Hall and Bennett 1956); finger-force measurement (Amis 1987, Chen 1991); muscle force minimisation (Sancho-Bru et al. 2003), and hand anthropometrics (Grant et al. 1992, Oh and Radwin 1993, Johnson 1993, Yakou et al. 1997, Blackwell et al. 1999, Garneau and Parkinson 2010, Seo and Armstrong 2008). A few studies have also used two or more criteria: finger-force measurement and muscle activity (Ayoub and Presti 1971, Grant et al. 1992, Blackwell et al. 1999); subjective comfort rating, finger-force measurement, and electromyographic efficiency during muscle activity (Kong and Lowe 2005). The broad varieties of criteria used for determining optimal cylindrical handle have also dictated the usages of different methods.
In our study ten male subjects with no hand injuries or disorders were used to obtain the DHHMs for each subject. In order to calculate the optimal diameters for the pre-handle, the following anthropometric measurements were performed on the subjects: lengths of the index, middle, ring, and little fingers from the hand’s wrist crease; fingertip lengths of the thumb, the index, and middle fingers together with the inside grip breadth between the index and middle fingers. Additionally the widths of each finger were measured for obtaining the corresponding section sizes for the pre-handle.

We evaluated and compared recent mathematical models for determining optimal diameters for the development of the pre-handle. The mathematical model from authors Seo and Armstrong (2008) was extended into the equation for a variable handle diameters of the index and middle fingers according to Garneau and Parkinson (2010). It was assumed, that optimal handle diameters could also be obtained also for the ring finger and little fingers using the relationship between the length of the index finger and the ring finger and little fingers. The obtained diameters were verified according to the equation for optimal handle diameter from the study of Kong and Lowe (2005). The diameter difference were calculated and proved to be negligibly small.

2.2 Optimal cylindrical pre-handle with variable diameters

Calculated diameters were used to manufacture customised optimally-cylindrical pre-handles with variable diameters; made from hard polyurethane. These cylindrical pre-handles with variable diameters were tested and it was shown that the calculated diameters were correct. This was because; as calculated; there was an overlap of the thumb’s fingertip with the index fingertip and middle fingers (Fig. 1).

![Fig. 1: Testing the optimally cylindrical pre-handle with variable diameters.](image)

2.3 Manufacturing the outer hand mould

In order to obtain the shape of the hand in its optimal power grasp posture with undeformed soft tissue, outer hand moulds were manufactured to maintain the diameters and shape of the hand when softly holding the corresponding optimal cylindrical handle with variable diameters. The outer-hand moulds were manufactured by two physiotherapists at The Institute of Physical and Rehabilitation Medicine of the University Medical Centre Maribor. The orthotic material Orfilight® (Orfit Industries, Belgium) was used with thickness of 2.5mm and micro perforation, which has the ability of moulding to anatomical contours. The moulds were shaped on the dorsal side of a hand softly holding the corresponding optimal cylindrical handle with variable diameters. The hand was in a neutral position according to ergonomic recommendations. After the shapes of the moulds were satisfactory, straps were added for hand and hand-opening fixation (Fig. 2).
2.4 MRI
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 subject’s scanning position was HFDR (Head First-Decubitus Right) with the extended hand. The used coil was a one-channel HD Knee/Foot Coil that allowed for the best positioning of the hand during the scanning. Prior to the scanning, the optimal cylindrical pre-handle with variable diameters had been used to finely adjust the correct size of the corresponding outer-hand mould. This optimal cylindrical handle with variable diameters was removed during the scanning in order to obtain undeformed soft tissue. The slice thickness was set at 1mm to avoid any unnecessary small anatomical structures and surface details. The image area was 512x512x121 pixels. The scanning time was about ten minutes. The subjects were told to hold their hands in open-positions 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.

2.5 Segmentation and 3D reconstruction
A professional medical imaging and editing software Amira® 5.3.3. (Visage Imaging) was used for the segmentation and 3D reconstruction of the DICOM images. Segmentation was performed using the threshold technique, since only the surface of the hand is needed and no differentiation in anatomical structure of the hand is necessary. Segmentation was done with a Label/Voxel module and a threshold value of 200, which proved to be the best value for obtaining the required segmentation. Small inclusions and segmentation errors were corrected by ‘remove islands’ and ‘fill holes’ commands. In order to achieve a smoother surface, a ‘resample’ module was added to the segmentation and 3D reconstruction process. The result was a smooth 3D representation of the subject’s hand in the power-grasp posture (Fig. 3).
2.6 Power-grasp tool-handle’s shape determination
STL files obtained within Amira® software were imported into CATIA® V5R20 (Dassault Systems®). The mathematically-defined volumetric model was defined based on generated surface model out of the STL file. In order to achieve the optimal handle for power-grasp posture, an elliptical cylinder was modelled in CATIA®. The size and the position of the cylinder were determined so as to fully overlap the palmar empty volume created by the hand during the optimal power grasp posture (Fig. 4).

Fig. 4: 3D hand and cylinder in overlapping position.

To get the handle based on DHHM, Boolean operation “Remove” was used that removed the cylinder model volume, and which overlapped with the hand-model volume. Additional smoothing of the sharp edges was performed to prevent injury on the handle. The resulting handle can be seen in Fig. 5.

Fig. 5: Tool-handle based on a DHHM.
2.7 Manufacturing of tool handles
In order to evaluate the optimally-cylindrical handles against those handles based on DHHM, both types were manufactured for each subject using rapid prototyping technology. The diameters of the cylindrical handles were determined based on the mathematical model that was also used for determining the shape of the handle based on the DHHM. All the handles were manufactured with a 3D printer using black ABS plastic with a smooth surface finish.

2.8 Task and measurement of subjective comfort rating
The subjects were instructed about the measurement procedure. They were told to stand comfortably with elbows at ninety degrees and wrists in neutral positions. They were asked to perform five tasks of gripping the DHHM-based handle for one minute each time using their preferred normal grip-force whilst applying a push-force of 50N on the handle mounted into a force-gauge. In this way a standardised and more generalised simulation of a common task using hand-tools was performed. This was assumed, as most tasks that require power or pistol-grips cause normal forces on the hand's surface. The same task was also performed by each subject using a corresponding cylindrical handle. In order to compare and evaluate the newly-developed and manufactured handles based on DHHM with the cylindrical handles, the subjects were given a subjective questionnaire regarding comfort-rating immediately after gripping both handles. This questionnaire was adapted based on a paper of Kuijt-Evers et al. (2007), as a continuum scale tends to deliver the best results in terms of sensitivity. The subjects rated each handle's comfort descriptors and overall comfort-rating on a scale containing 7 discrete levels (from 1 = totally disagree to 7 = totally agree) based on their perceived subjective responses for each handle. The questionnaire used for collecting the subjective data can be viewed in Tables 1 and 2.

3 Results and discussion

3.1 DHHM method's verification
Measurements on the obtained handles based on DHHM in CATIA® showed, that the optimal diameters for each finger were withheld by the outer-hand moulds within small deviations during the MRI. Therefore, according to Seo and Armstrong (2008), the maximum grip-force can be exerted that can increase the user performance whilst using the handles designed with DHHM. Subjective comfort-rating based on the subjects’ preferences regarding grip-diameter size is also increased since there are small deviations according to study from Kong and Lowe (2005).

The manufactured tool-handles based on the DHHM were also compared to the corresponding optimally-cylindrical handles regarding the contact area. The mean contact area of the optimally-cylindrical handles were $A_{opt\_ca} = 80.80cm^2$. On the other hand, the contact area measured on the handles designed based on DHHM was $A_{opt\_cust} = 101.34cm^2$. An increase in contact area of 20.54cm² could be observed that was an increase of over 25%.

3.2 User evaluation - subjective comfort rating
The mean values and standard deviations were calculated based on the data obtained from the subjective comfort-rating questionnaire. A dependent samples T-test was conducted to examine whether there was a significant difference between the cylindrical handles and the handle based on the DHHM design in relation to subjective comfort predictors and overall subjective comfort-ratings. The mean values with standard deviations, together with the statistical significances of the comfort predictors and overall comfort-rating, can be seen in Fig. 6.
The T-test revealed that comfort descriptors ‘Fits the hand’ and ‘Offers a nice grip feeling’ are statistically significant different at the p<.05 between the cylindrical handles and handles based on DHHM. Both comfort predictors were rated higher for the handle based on DHHM than the cylindrical handle. This can be explained by the anatomical shape of the handle based on DHHM, because it considers the optimal power-grasp posture; with optimal diameters being achieved for each finger which assures the maximum voluntary contraction of fingers. Therefore the handle based on DHHM provided better fitting for the tested subjects. This was impossible with the cylindrical handle, since it took only one finger’s optimal diameter determination into account.

The cylindrical handle is axle-symmetrical and therefore provides several feasible gripping positions, whilst the handle based on DHHM provides only one feasible gripping position. Nevertheless, the rating of the comfort predictor ‘Is easy in use’ is statistically not significant different between both handles.

The stability of the tool-handle based on DHHM has been greatly increased because the majority of the forces and moments have been transferred over to the anatomical handle-shape and much less with the friction between the handle material and skin. In order to provide stability whilst holding the cylindrical handle, the normally exerted finger-force has to be reasonably high to prevent slippage, and rotation in the direction of the handle’s axis. High local and overall contact pressures occur from highly exerted normal forces that can cause discomfort and also acute disorders and CTD (i.e. blisters, inflamed skin, cramped muscles, …). When using tool-handle based on DHHM; lower normal gripping-force can be exerted in comparison to the cylindrical handle, and the tool can be stabler held in the hand. Therefore, the handle based on the DHHM also prevents excessive tensile and shear stresses on the skin and subcutaneous tissue, because the forces and moments are transferred with the shape of the handle and not by the soft tissue. This is clearly evident from the comfort predictors ‘Has a good
force and moment transmission', 'Needs a low grip force for stable grip'. Both comfort predictors showed significant difference between the cylindrical handles and those handles based on DHHM at p<.01.

In comfort predictor 'Has a good friction between the handle and hand', it is evident that the subjects were referring to the friction caused by the forms of the handles and not the material friction between hand and handle, since both handles were manufactured with same material and same surface finish. A statistically significant difference could be observed between the cylindrical handles and those handles based on DHHM for this comfort predictor.

Subjective comfort-rating that describes the handle's visual appearance and quality ('Is a high quality handle') showed a significant difference between both handles at p<.01, and was rated higher for the handle based on the DHHM than the cylindrical handle. The higher rating of the handle based on the DHHM for this subjective comfort predictor can be explained by past user experiences and expectations because hand-tools; and consequently those handles with good fit for the user; have higher functionality and thus performance. Although the handle’s appearance only indirectly affects the comfort, it has significant impact on buying decisions.

The causes 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, thus causing ischemia. However this effect is strongly time-correlated. Therefore; the short gripping times of a handle that produce high contact pressure on soft tissue do not evoke numbness and lack of tactile feeling. Therefore also comfort predictors 'Causes numbness and lack of tactile feeling' and 'Causes cramped muscles' were statistically not significant different between the cylindrical handle and the handle based on DHHM. This can be explained by the measurement procedure, where the test subjects gripped the tool-handle five times each time for one minute. Therefore it can be concluded, that longer gripping times or real hand-tools with tasks that require longer gripping times should be used when evaluating the comfort predictors.

The subjects also evaluated the overall subjective comfort-rating whilst gripping both handles. The T-test revealed that there was a statistically significant difference between the cylindrical handle and the handle based on DHHM at p<.01. Thus the anatomically-shaped handle based on the DHHM can be considered as more comfortable overall in comparison with the cylindrical handle. This was also expected, since most subjective comfort predictors indicate that those tool-handles based on DHHM are more comfortable than the cylindrical handles.

3.3 DHHM evaluation
The 25% increase in the contact area for those handles designed on DHHM can be attributed to the fact that these handles follow the shape of the hand during its optimal power-grasp posture and thereby provide greater contact area. According to Seo and Armstrong (2008) the greatest contact area in their study was obtained with diameters of 51mm and 58mm with cylindrical handles, which is in contradiction with the size of optimal diameters for grip-force and comfort maximisation that suggest smaller diameters. It is obvious, that contact area maximisation is impossible with cylindrical handles when considering an optimal diameter for maximising grip-force exertion and comfort-rating. Since the contact pressure depends not only on the grip-force but also on the contact area, it is reasonable to provide greater contact area in order to lower the contact-pressure. The non-linear visco-elastic properties of skin and subcutaneous tissue lead to an exponential rise in contact-pressure with a higher degree of tissue deformation. High overall and local contact pressure can be avoided with an anatomical shape of the handle and, therefore, also a greater contact area. Research into tissue deformation under mechanical stresses using finite element analyses has shown that the shape that follows anatomical shape of the hand results in much lower contact pressures. Therefore the handle introduced during this study is more likely to prevent those CTDs that are pressure-dependent, and provide a greater comfort-rate than a cylindrical handle, as has been shown by user evaluation.
Some heavy tasks require the use of protective or anti-vibration gloves to avoid acute disorders and CTD. The thicknesses of the gloves can vary, and thus the resulting effective grip diameter of each finger varies also when gripping the tool-handle using bare hands. However the relatively small thicknesses of the gloves compared to the optimal grip diameters effects the overall grip diameters only slightly, which therefore has a small effect on the maximum voluntary contraction forces of the fingers. On the other hand, all benefits using gloves (peak contact-pressure reduction, vibration reduction, shear-force reduction,…) would still be maintained. Nevertheless, the subjective comfort-rating would be affected, since the gloves reduce the tactile sensing and; therefore; also subjective feelings. In order to compensate for the grip’s diameters when using gloves, the DHHM could be adapted with a scaling function that would allow the designer to choose whether the tool-handle would be used bare-handed or using gloves. The predicted mean thickness of the glove could be the input data for the scaling function of the tool-handle. In order to fully investigate the importance of using gloves with tool-handles based on DHHM this issue should be the subject of broader investigation in the future.

Many of existing biomechanical DHMs or DHHMs are complex regarding usage, thus preventing broader dissemination. The static shape DHHM developed during this study can be used by designers and engineers as it enables simple manipulation inside CAD software of choice. It also does not require an ergonomics specialist, since the obtained DHHM is based on an optimal grasping-posture that allows for the direct modelling of anatomically-shaped tool-handles. Most of the dynamic DHHMs with autonomous grasping are intended for evaluating and analysing an existing CAD designs inside the virtual environment. If the produced autonomous grasping of the DHHM is feasible and realistic, ergonomics design errors can be identified and design solutions can be proposed. This iterative design process is repeated until the design does not meet the desired level of ergonomics. On the other hand, direct development of tool handles based on the obtained DHHM within existing CAD tools becomes an integrated process, resulting in increased time efficiency and tool handles with improved ergonomics, without the need for comprehensive knowledge of ergonomics by the designer. Unnecessary become also physical prototypes for the purpose of ergonomic analyses. Following improved product ergonomics, the market value of the product is increased, thus enhancing the competitiveness of the product on the market.

Future work should also consider user-testing of those tool-handles based on the DHHM using a pressure-mapping system for identifying those contact forces and pressure zones that exceed the PDT and SD values. Based on the obtained data, optimisation of handle-size and shape could be conducted for limiting those pressure-peaks below acceptable limits. Correlations could also be determined between subjective comfort-rating and local and overall pressures. The resulting methods for the development of the DHHM also provide the possibility for future tool-handle shape determinations and optimisation for a broader population. In regard to that purpose; more subjects should be considered when modelling a parametric DHHM, which would allow for a direct generation of tool-handles for a targeted population. The findings of this research could also be combined with a dynamic DHHM for providing verification and validation of the proposed power grasp. In this way a comprehensive DHHM could be developed for performing ergonomic analyses and enabling direct designing for improved ergonomics.

4 Conclusion
This paper presented a different approach to tool-handle design. An anatomically-accurate static DHHM was developed based on MRI and an optimal power-grasp posture with undeformed soft-tissue. The proposed methods allow for the direct development of tool-handles with anatomical shapes and sizes that increases the maximum voluntary contraction of fingers, maximises the contact area, and, thereby lowers the local and overall contact pressures, and increases the subjective comfort-rating.
References


