Odprtokodna programska oprema za medicinske slike: študija primera na podlagi interdisciplinarne inovativne zasnove izdelka

Open-Source Software in Medical Imaging: Case-Based Study with Interdisciplinary Innovative Product Design

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Ključne besede:
ročaj orodja, odprtokodna programska oprema, ergonomija, segmentacija, medicinske slike, 3D model roke

Key words:
tool handle, open source, ergonomics, segmentation, medical imaging, 3D hand model

Članek prispel / Received
14.03.2012

Članek sprejet / Accepted
03.05.2012

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Izvleček

Namen: *V zadnjem času je bilo razvitih precej celovitih rešitev odprtokodne programske opreme za medicinske slike, ki ponujajo zmogljiva orodja za slikovno upravljanje, vizualizacijo, skladiščenje in analizo. Namen članka je predstaviti odprtokodno programsko opremo za delo z medicinskimi slikami in njene značilnosti ter jo primerjati s komercialnimi rešitvami.*

Metode: *Predstavljen je primer razvoja optimalne velikosti in oblike ročaja ročnega orodja s pomočjo brezplačne odprtokodne programske opreme »3D Slicer®«.*

Večina avtorjev priporoča valjasto oblikovanost ročajev, da bi povečali udobje in učinkovitost uporabnika ter preprečili kumulativna travmatična obolenja, vendar optimalna oblika ročaja še ni bila ugotovljena. Namen raziskave

Abstract

Purpose: *Recently, comprehensive open-source software (OSS) solutions for medical images have been developed. They offer powerful tools for the management, visualization, storage and analysis of images. The purpose of the present study was to present the features and use of OSS in comparison with commercial software solutions when evaluating medical images.*

Methods: *A case study of the development of a tool handle of optimal size and shape using the free OSS "3D Slicer" is presented. Many authors recommend cylindrical-shaped handles to increase comfort, performance and to avoid cumulative trauma, but none have considered the optimal shape of the handle. Hence, we derived a method for obtaining*

je predstaviti metode, s katerimi je mogoče pridobiti obliko ročaja v optimalni drži roke za krepki oprijem s čim bolj optimalno porazdelitvijo pritiska na mehka tkiva.
Uporabili smo magnetno resonančno preiskavo in individualno izdelan kalup, ki je ohranjal optimalno držo roke med preiskavo. Program »3D Slicer« je bil uporabljen za segmentacijo in 3D rekonstrukcijo na osnovi MR slik. 3D model roke je bil nato »izvožen« v komercialni program za računalniško podprto konstruiranje optimalnega ročaja orodja.
Rezultati: *Meritve premerov na 3D rekonstrukciji so pokazale, da so bili položaji zadržani z le majhnimi odstopanji, kar maksimizira največjo silo kontrakcije prstov. Tako oblikovan optimalni ročaj zagotavlja 25 % večjo kontaktno površino v primerjavi z optimalnim valjastim ročajem in s tem zmanjšuje tudi kontaktne tlake, kar povečuje učinkovitost in udobje ter (zelo verjetno) preprečuje kumulativna travmatična obolenja.*
Zaključki: *Prikazan primer potrjuje ustreznost odprtokodne programske opreme za medicinske slike kot (večinoma) brezplačno in učinkovito orodje, podobno kot (neredko drage) druge komercialne rešitve.*

an optimally shaped tool handle based on the power grip hand posture and non-deformed soft tissue.
During magnetic resonance imaging (MRI), an outer hand mold was used to maintain the optimal hand posture. 3D Slicer was used for segmentation and 3D reconstruction of MRI. A three-dimensional (3D) hand model was exported to a commercial program for computer-aided design for the optimal tool handle.
Results: *Measurements of the diameters on 3D reconstruction showed that the position of fingers wasere withheld within small deviations, which maximized maximum finger force exertion. An optimally shaped handle this way provided 25% higher contact area compared with the optimal cylindrical handle. It therefore reduced contact pressure, increased performance and comfort and could probably prevent disorders due to cumulative trauma.*
Conclusion: *This case study supported the use of OSS for medical imaging as a powerful and (mostly) free tool comparable with (usually expensive) commercial solutions.*

INTRODUCTION

Non-invasive techniques are developing rapidly as excellent tools for better understanding of biological systems and for improved diagnostics and therapeutic strategies. Huge advances have been realized in medical imaging. Advances in technology and computing have led to higher resolutions and several methods with faster and better processing through the use of "cloud computing" (1, 2). Medical imaging technologies are continuously improving, and new technologies have been developed from empirical methods.

This huge development in medical imaging means that comprehensive software for handling large amounts of digital output which enables better management, visualization, storage and analyses is needed (2). With high-resolution images obtained from high-end magnetic resonance imaging (MRI), computed tomography (CT) and ultrasound (US) machines, three-dimensional (3D) volume-rendered images are available that present human anatomy in a realistic manner (3, 4). These volume-rendered images can provide good perception of spatial relationships between different anatomical structures and good perception of topology (4). Another domain of medical imaging is functional and molecular imaging, such as positron emission tomography (PET), in which biological processes can be observed. Anatomical data from CT or MRI can be combined with images from other imaging methods, which can provide a whole new dimension to the data (5). Additionally, if images are collected for a longer period, another dimension can be added. These 3D (4D or even 5D) extensive data requires the use of high-end software.

Therefore, commercial medical imaging software solutions have been developed by different companies to provide tools for the visualization, manipulation, storage and analysis of medical images (6). Currently available commercial software for medical imaging include: Amira (7), Huygens (8), Analyze (9), AVS (10), IDL (11), Image Pro (12), iNtuition (13), Imaris (14), MetaMorph (15), Mimics (16), AxioVision (17), Vitrea (18), Syngo.via (19), IntelliSpace Portal (20) and Dexus (21).

In recent years several research laboratories have developed non-commercial medical imaging software which incorporates specific functionalities that cannot be found in commercial software. These non-commercial programs are mostly released as open-source software (OSS) and are discussed in the following section.

OSS and its importance

The origin of OSS lies in the non-commercial world because individuals wanted to freely share their creations, promote their redistribution, allow others to modify them, and incorporate improvements made by others. To legally describe the copyright situation, different types of open-source licenses were defined. These ranged from the most loosely defined licenses such as public domain, Berkeley Software Distribution (BSD) or Massachusetts Institute of Technology (MIT) license to copyleft-oriented ones such as the GNU General Public License (GNU GPL) (22) or restricted licenses such as Creative Commons. The most evidently successful OSS is the Linux operating system (23), which was developed under GNU GPL (22). The development of OSS for medical imaging has broadened in the last decade, and several open-source programs have been developed: 3D Slicer (24), OsiriX (25), VolView (26), ParaView (27), MeVisLab (28) and SCIRun (29).

The advantage of OSS in comparison with commercial software is that the programming source code is made available to the public under the terms of the license. Open-source licenses usually allow users the use of software freely for any purpose, adapting the software to their needs, making derivates of the software, and to distribute and link to existing software (6). Many scientific discoveries and progress in medical imaging can be attributed to the OSS community because the source code is available to users and other developers. Therefore, the OSS is dynamic and their solutions can adapt and evolve quickly to be more applicable. Conversely, copyright holders of commercial closed source software do not allow access to their programming source code, which is usually developed by just a few developers. It is therefore more static and requires a longer time to include new features. However, commercial software has also contributed appreciably to advances in medical imaging because the commercial type of marketing allows for higher development costs. Most companies that develop medical-imaging software try to determine which features will be demanded, and this is based on feedback they get from users (5). This traditional approach is not very innovative, and therefore new features take a long time to be implemented into commercial software. Commercial software is market-driven, so there is very little room for experimentation and adopting of non-conventional ideas, which contribute to scientific breakthroughs.

Standardization

Standardization is very well established in the field of file-format support with OSS (6). This enables different packages to work with other files, which provides general applicability (30). Many commercial software companies are forcing their users into closed software "ecosystems". Each company has its own custom format for storing data in the files such that manipulation (opening, editing, saving) with competitive software is not possible. Therefore, companies are forced to develop and provide comprehensive medical-imaging software solutions that meet the needs of the industry to retain the market share.

Commercialization and clinical usage

Most of the open-source frameworks are developed for research purposes, so they include a "clinical use is neither recommended nor advised" clause into the terms of the license agreement. Hence, the development team does not take responsibilities for problems that could arise with misuse or from programming errors (31). However, clinical use is not prohibited although, if problems arise, the responsibility falls with the user of the framework and not the developers (32). For obtaining the mark "for clinical use", the medical imaging software must be rigorously tested and evaluated before its release, and must obtain certification through the US Food and Drug Administration (FDA) or similar institution. In some cases, Institutional Review Boards can approve software which is not intended for clinical use, so OSS can be used in clinical practice.

In some cases, developers of freely available OSS also develop a commercial version of the software. In most cases, such commercialization requires adherence to strict regulations as well as rigorous validation and testing procedures, which provides a base for certification under government law.

Companies that commercialize OSS provide integration, certification, quality insurance, maintenance, user training and support whereas software developed only by the community cannot provide these services (5). For example, OsiriX MD (33) OSS has been cleared for clinical use by the FDA (34); it includes a user manual and provides email support.
In some cases, commercial vendors adopt open-source codes or establish partnerships with the OSS community such that the companies can be involved into the development of OSS for the benefit of both parties (6). Developers of commercial software therefore benefit from the OSS community, who can adopt and implement innovative solutions faster and with minimal risks (5).

Support for OSS

When providing support for the software (instructions, manuals, user support), commercial software is usually better than OSS because comprehensive support which is included in the license or which can be purchased is provided (6). In general, OSS cannot provide such support, but provides different communication and collaboration platforms for the community. However, such support is usually voluntary, so the reliability of this support is not on the same level as that with commercial software. In recent years, innovative market approaches with different funding agencies have led to the establishment of comprehensive support services for some of the OSS solutions. A combined business model whereby the software is freely accessible, but professional support has to be bought separately, is also available.

MATERIALS AND METHODS

As described above, many types of OSS provide comprehensive tools for the manipulation and analysis of medical images. To demonstrate the power of OSS for medical imaging, a case study based on the innovative design of a tool handle is described in this section.

During this research, all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed.

Design of a tool handle

The designs of tool handles have been extensively researched. Authors have provided recommendations and mathematical models for the design of cylindrical handles to increase performance as well as to avoid discomfort and disorders due to cumulative trauma (35–41). None of these authors considered the optimal shape of the handle, which could also improve ergonomics (39).

The aim of the present study was to provide methods to obtain an optimally shaped tool handle for a test subject. Therefore, an outer hand mold was manufactured based on a handle with variable diameters according to each finger to immobilize the hand in the optimal power grasp posture. To obtain a 3D shape of the hand with non-deformed soft tissue, MRI was undertaken with the outer hand mold attached. Segmentation and 3D reconstruction was conducted in the medical imaging OSS "3D Slicer". The tool handle with optimal size and shape was then modeled in commercial computer-aided design (CAD) software.

Figure 1. Outer hand mold.

Imaging procedure

MRI was carried out in the Department of Radiology of University Clinical Centre Maribor (Maribor, Slovenia). The outer hand mold (which was manufactured to maintain the correct power grasp hand posture) was fixed with foam (which prevented hand movement during imaging). The subject was told to hold his/her hand in the open position while fully touching the mold during imaging to maintain the appropriate diameters and shape of an optimal power grasp (Figure 1).

A Signa HDxt 3.0T system (GE Healthcare, Piscataway, NJ, USA) was used to obtain the medical images. The used coil was a one-channel HD Knee/Foot Coil which allowed the best positioning of the hand during imaging (Figure 2). MRI was done with slice thickness set to 1 mm. The image area was 512 × 512 × 121 pixels. The scanning time was ≈15 min. Images were provided in the Digital Imaging and Communications in Medicine (DICOM) format.

Figure 2. *Positioning of the test subject for MRI.*

3D Slicer

In the present study, the free medical imaging OSS 3D Slicer was used to manipulate and edit the obtained DICOM images (24). 3D Slicer is comprehensive medical-imaging software which incorporates considerable robustness, flexibility and functionality for visualization and image analyses (42). It is available on multiple platforms such as Windows, Mac OSX and Linux. 3D Slicer is not intended for clinical use, but the source code is available as a BSD-style license, under which there are no reciprocity requirements, no restrictions on use, and no guarantees of performance (32).

Segmentation and 3D reconstruction

In the present study, the latest stable version (4.0) was used. The volume information from DICOM images was interpreted incorrectly. There-

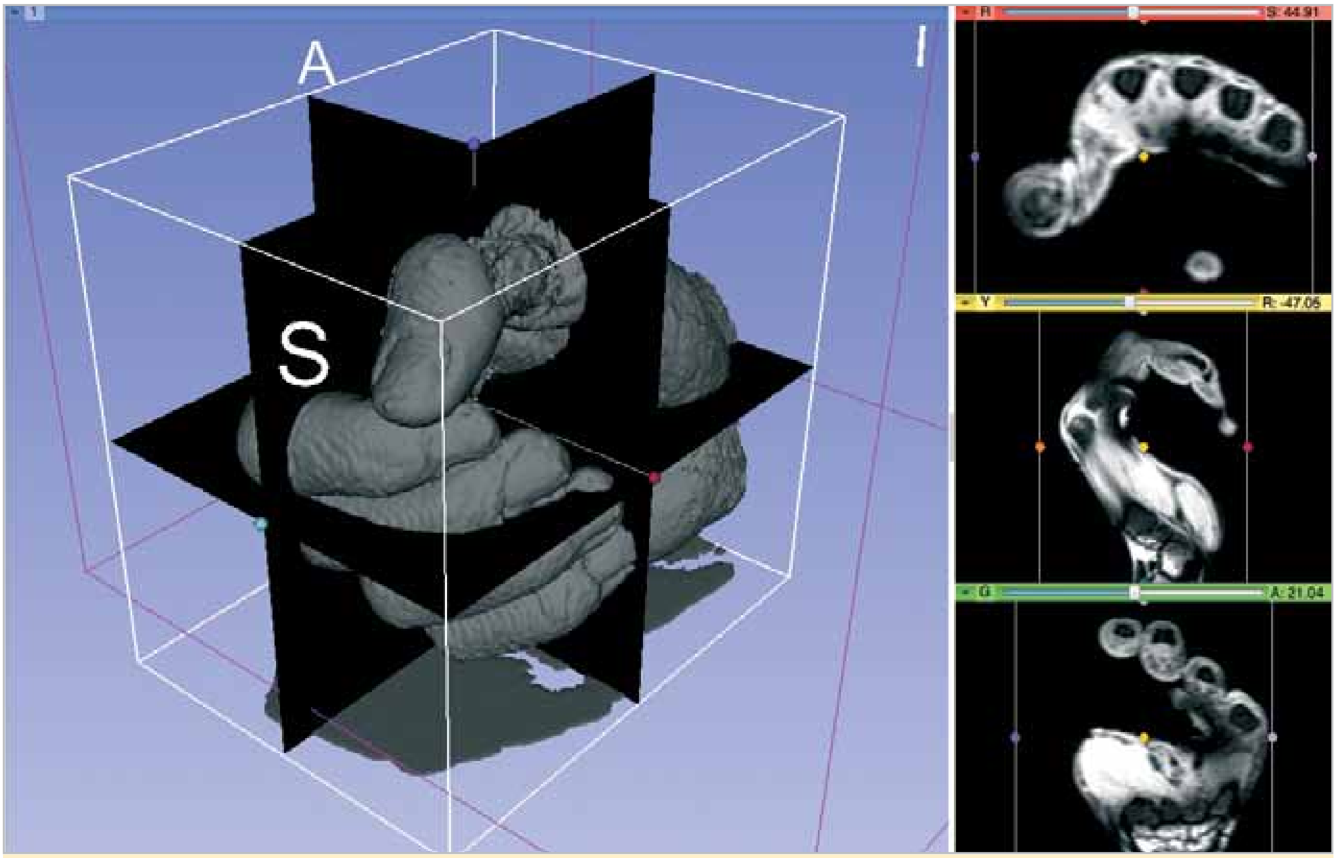

Figure 3. *Three-dimensional reconstruction in the 3D Slicer*

fore, slices in axial and coronal planes were visualized with an inappropriate aspect ratio. The module "Volume" was used to correct this problem.

Differentiation in anatomical structures was not necessary for obtaining the tool handle, so a Grayscale Model Maker module was used to make a fast 3D reconstruction based on the threshold method. Parameters for the 3D reconstruction were determined based on experience and, after some iterations, a satisfactory 3D reconstruction was obtained. The 3D hand was evaluated visually for imperfections. It was clearly visible that the surface was very detailed, but it was rough, which was a result of the noise of MRI (Figure 3).

A Gaussian Blur Image Filter with a sigma factor of 1.2 was used to smoothen the images and therefore also the 3D-reconstructed surface. The result was a 3D-reconstructed hand with a smoother surface, which was a good base for obtaining the optimal tool handle. Segmentation based on the threshold method did not segment the area of the proximal phalange of the thumb (Figure 4). Errors could be attributed to the obtained MRI because the difference in grayscale value between the anatomical structure and the space (background) was not clearly visible. Hence, manual segmentation was undertaken (Figure 5). The histogram on the images was adjusted so that the contour of the thumb was clearly visible to conduct the manual segmentation.

After manual segmentation, the hand was again 3D-reconstructed and evaluated. This proved to be successful because the surface of the proximal phalange of the thumb was now smooth and connected. It also presented the anatomical structure of the subject´s hand in its optimal power grasp posture (Figure 6). After the 3D model of the hand was deemed satisfactory, it was exported in the stereolithography (STL)

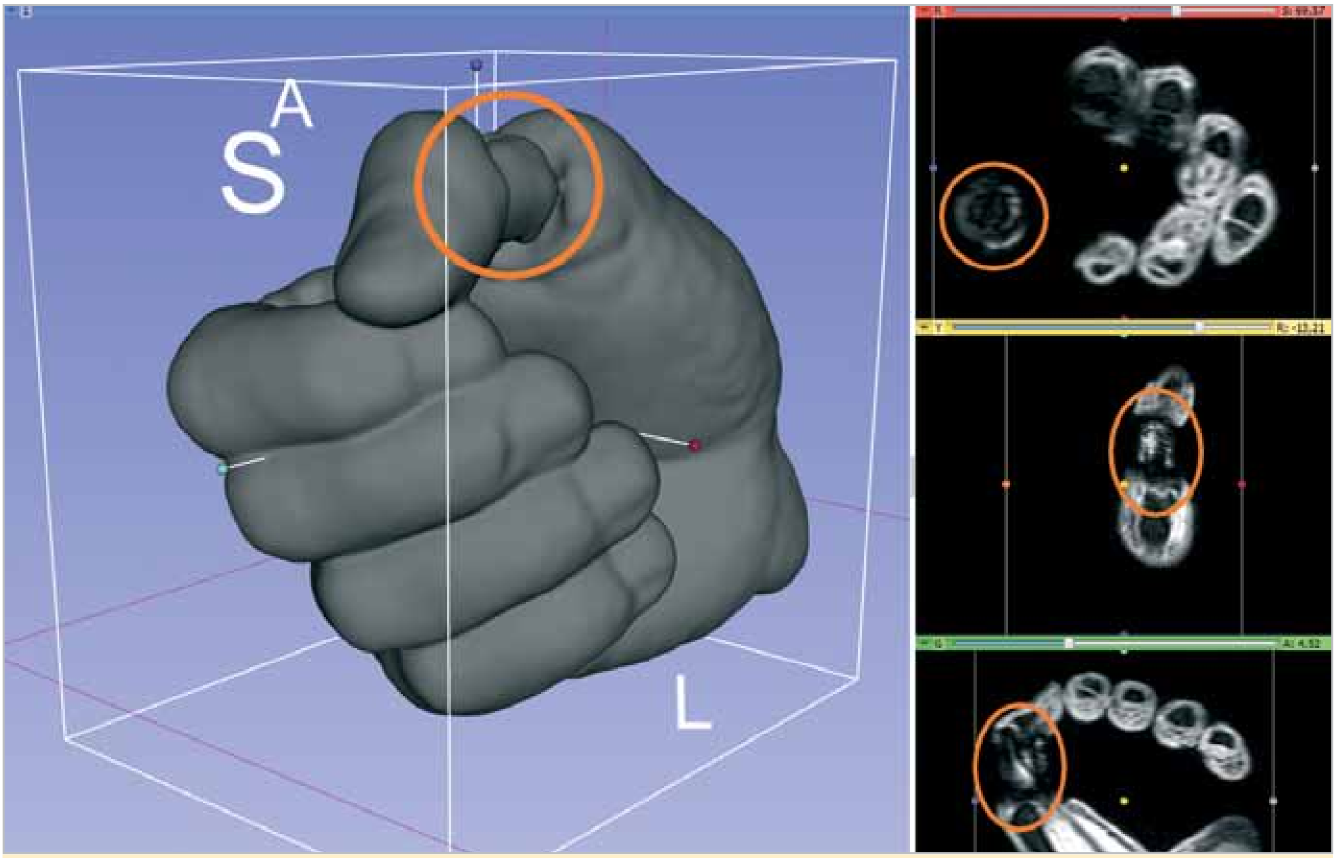

Figure 4. *Three-dimensional surface model after smoothing and errors in segmentation.*

file format (which is a file format in the domain of rapid prototyping).

The STL file obtained in 3D Slicer was imported into CAD software. The 3D hand model was edited and a mathematically defined volumetric model generated. An elliptical handle was modeled with the size and position according to the empty ventral opening of the obtained 3D hand (Figure 7). A handle with optimal shape and size was then obtained with a Boolean operation, which removed the cylinder model volume that was in overlap with the hand model volume (Figure 8).

To ascertain the clinical benefit of individualization of the tool handle, the contact surface area was measured virtually and compared with an optimal cylindrical handle. Therefore, an additional optimal cylindrical handle was manufactured using hard plastics. The cylindrical handle was covered with 80 g/m^2 white paper with a printed black square in a predetermined area. The hand was covered with thin layer of black ink and the handle gripped with maximum grip force for 5 s. The paper was then removed and scanned with a flatbed scanner at high resolution. The area of the transferred ink was measured with a selection made by the color range tool within Adobe® Photoshop® CS4 (Adobe, San Jose, CA, USA) and was compared with the area of the predetermined black square.

RESULTS

We created a tool handle which took into account the shape of the hand to enable an optimal power grasp posture with non-deformed soft tissue. This methodology provided the best fit for the subject's hand.

The measured mean contact area of the optimal cylindrical handle (Aopt|cir) was 80.80 cm^2. The mean

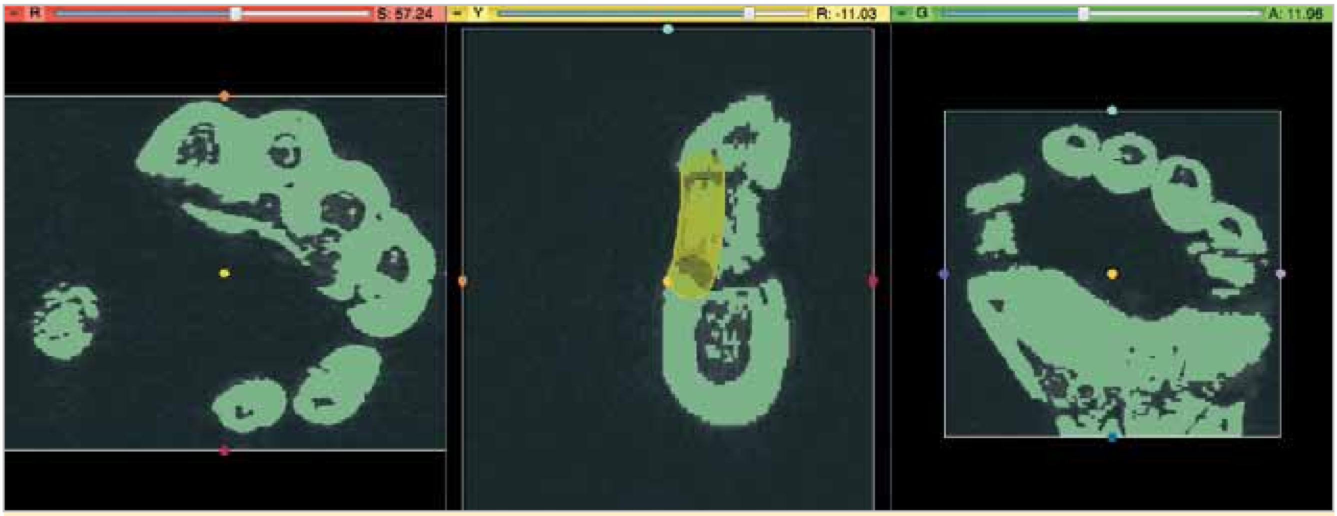

Figure 5. *Manual segmentation of the proximal phalange of the thumb.*

Figure 6. *Three-dimensional reconstruction after manual segmentation.*

Figure 7. *Three-dimensional hand and elliptical cylinder in the overlapping position.*

contact area measured virtually on the obtained custom shaped handle (Aopt|cust) was 101.34 cm^2. An increase in contact area of 20.54 cm^2 was observed (an increase of >25%).

A rapid prototype was manufactured to assess the custom-made handle. The opinion of the test subject with regard to the stability and comfort of the custom-made handle was compared with that of the optimal cylindrical handle. The test subject stated that the custom-made handle was significantly more stable and comfortable.

DISCUSSION

In the human-centered design described in the present study, medical imaging was the only viable option for acquisition of a 3D hand surface with non-deformed soft tissue to develop a tool handle of optimal size and shape. The development method took into account the shape of the hand in the optimal power grasp posture and therefore provided the best fit for the subject´s hand. Therefore, the hand was "fixed" with a custom-made orthotic mold during imaging. DICOM images were successfully recognized

Figure 8. *A handle with optimal shape and size.*

by 3D Slicer, but the aspect ratio on the axial and coronal images was incorrect. This could have been due to inappropriate reading of the DICOM header (in which information on image spatial relationships is stored). To determine if this was a DICOM file format issue or medical imaging software issue, the same images were also loaded in commercial software (Amira and Mimics) where the aspect ratio was set correctly. However, the incorrect aspect ratio in 3D Slicer could be readily corrected in the Volume module. Preliminary 3D reconstructions based on the threshold method showed that the proximal phalange of the thumb was not segmented correctly due to differences in grayscale values between the anatomical structure and space (background). The lower quality of MRI could be attributed to a long imaging time of ≈15 min and inappropriate fixation of the subject´s hand due to specific imaging purposes. The test subject stated that, after ≈10 min, holding the hand open while fully touching the mold was difficult because the muscles started to tire and therefore relaxed and contracted asynchronously. This was reflected in slight movements of the hand, which affected the accuracy of the results and reduced image quality. Nevertheless, comprehensive manual segmentation tools in 3D Slicer allowed correction of this problem, and 3D reconstruction was conducted successfully afterwards.

The 3D-reconstructed hand was measured inside 3D Slicer to evaluate if the calculated optimal diameters for each finger (and therefore the optimal shape of the power grasp posture) was withheld by the outer hand mold during MRI. The diameter of each finger influences greatly the maximum possible exerted finger force and subjective comfort rating, so ensuring that the diameters are correct is crucial. Measurements have shown that diameters were withheld within small deviations. Therefore, it can be assumed that the 3D-reconstructed hand represented the optimal power grasp posture, which was the basis for creating an optimally shaped tool handle.

The increase in the contact area observed in calculations was expected because the optimally shaped handle followed the anatomical shape of the hand in the optimal power grasp posture and therefore the contact area was maximized. It is clear that maximization of the contact area was not possible with cylindrical handles when considering the optimal diameter to maximize grip force exertion and comfort rating. Therefore, it could be concluded that maximization of the contact area was possible only when considering the anatomical shape of the hand in its optimal power grasp posture. Hence, a greater contact area could be obtained by lowering the overall and local contact pressure. The higher comfort rating could probably be attributed to the higher contact area and anatomical shape of the handle. This could also lead to prevention of disorders due to cumulative trauma (e.g., pressure ulcers, disorders due to vibration) and provide greater comfort than a cylindrical handle.

Utilization of interdisciplinary innovative methods based on medical imaging and free medical imaging OSS could enable determination of an optimally shaped tool handle with improved ergonomics.

In general, the commercial software used in medical imaging is too expensive for smaller institutions such as research laboratories in the developing world. The financial capacity of some institutions has decreased due to the economic downturn, so increasing numbers of institutions are reassessing their investments and trying to lower costs. Most OSS can be adapted to specific needs and usually provides the same powerful and comprehensive tools, so OSS could be an adequate and suitable solution in comparison with commercial software solutions.

ACKNOWLEDGEMENTS

We thank Professor Vojko Pogačar from the Faculty of Mechanical Engineering Professor Andreja Sinkovič from the University Medical Centre Maribor for establishment of the cooperation between these two institutions. We also thank the Department of Radiology for use of MRI facilities and to the Institute of Physical and Rehabilitative Medicine for creating the plastic mold.

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