



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, tendonitis, 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 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.

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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), tendonitis, etc. These CTDs account for about one third of the sick leaves of workers, resulting in high workers' compensations claims (Punnett and Wegman, 2004).

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The broad variety of powered and non-powered hand-tools has steered 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 80 kPa, 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 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 (30 mm) 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; 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-Pitarch 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.

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