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Mapping kinematic functional abilities of the hand to three dimensional shapes for inclusive design

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ABSTRACT

Loss of hand function can have adverse effects on an individual's ability to maintain independence. The ability to perform daily activities, such as food preparation and medication delivery, is dependent on the hand's ability to grasp and manipulate objects. Therefore, the goal of this research was to demonstrate that three dimensional (3D) modeling of hand function can be used to improve the accessibility of handheld objects for individuals with reduced functionality through informed design. Individual models of hand functionality were created for 43 participants and group models were developed for groups of individuals without (Healthy) and with reduced functionality due to arthritis (RFA) of the hand. Cylindrical models representative of auto-injectors of varying diameters were analyzed in 3D space relative to hand function. The individual model mappings showed the cylinder diameter with the highest mapped functional values varied depending on the type of functional weighting chosen: kinematic redundancy of fingertip pad positional placement, fingertip pad orientation, or finger force directionality. The group mappings showed that for a cylinder to be grasped in a power grasp by at least 75% of the Healthy or RFA groups, a diameter of 40 mm was required. This research utilizes a new hand model to objectively compare design parameters across three different kinematic factors of hand function and across groups with different functional abilities. The ability to conduct these comparisons enables the creation of designs that are universal to all – including accommodation of individuals with limits in their functional abilities.

1. Introduction

The capacity to perform many of the activities during daily living is dependent on the hand's ability to grasp and manipulate handheld objects. However, increased age has been shown to correlate with losses in the ability to use the hand (Ranganathan et al., 2001). In addition, ailments such as arthritis, stroke, carpal tunnel syndrome, and hand injury adversely affect hand function for millions of individuals (Helmick et al., 2008; Jackson, 2001; Luckhaupt and Dahlhamer, 2013; Roger et al., 2012). These conditions result in decreases in joint range of motion (ROM) and in the ability to generate forces with the hand (Carmeli et al., 2003). These decreases have been shown to lead to limited capacity to perform activities of daily living (Dellhag and Bjelle, 1999) and, consequently, loss of independence (Covinsky et al., 2008). In order to maintain the ability to manipulate objects as functional capability is lost, either the individual needs to adapt and use different strategies, or the object being manipulated must be designed to match the abilities of the person. As such, there is a need to understand interactions between the hand and the object.

Finger motions and force generations have been studied in depth as a means to understanding human motor control. Because the hand has so many possible degrees of freedom to control and it uses them to accomplish such a broad range of tasks, understanding how the hand completes each task is not trivial. Concepts such as finger synergies (Latash, 2010; Latash et al., 2007; Visser et al., 2002) and enslaving (Kim et al., 2008; Zatsiorsky et al., 1998) have been studied in detail as ways of explaining how the human body simplifies the complex tasks of controlling force production of a kinematically and kinetically redundant system. While these studies and many more advance the understanding of the control of the human hand, they lack direct transferability to 3D spaces in a way that can be used to inform object design.

Several models define the abilities of the hand in terms of reachable 3D spaces and have the potential to quantify hand–object interactions (Dias et al., 2009; Dragulescu et al., 2007; Johnson et al., 2010; Kuo et al., 2009). The weighted fingertip space (WFS) model developed by the authors is one such model that

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calculates the reachable spaces and weights the spaces according to kinematic functional abilities (Leitkam et al., 2013). The WFS model defines 3D reachable hand spaces using hand anthropometry and joint angles as input and then weights the reachable points to identify the (1) relative number of possible finger postures that allow a fingertip to reach each point, (2) range of possible orientations that the fingertip could assume at each point and (3) angular range of possible directions the fingertip could apply forces at each point. The WFS model has been shown to successfully quantify hand functionality for populations of individuals with and without reduced functionality of the hand (Leitkam and Bush, 2015). While these fingertip workspace models exist and have the potential to translate the 3D kinematic abilities of the hand into object design spaces, none have yet done so.

Accordingly, the goal of this research was to demonstrate that the WFS model can be used to determine the shape of a handheld object that best matches the kinematic functional abilities of individuals, including those with reduced hand function. Matching the object design to the hand's capabilities will lead to improved product designs so that individuals with reduced function can manipulate objects needed for everyday life and maintain independence.

2. Methods

2.1. Participants

Two groups of individuals were included in this research. The Healthy group consisted of 10 women and 12 men, ages 18–39 (mean 25.6, SD 5.8) without any reported injury or difficulty using their hands. The group with reduced functionality due to arthritis (RFA) consisted of 16 women and 5 men that were over the age of 65 (mean 72.6, SD 5.9) with self-reported cases of doctor-diagnosed arthritis. The Healthy group had an average hand breadth of 82.98 mm (SD 6.96 mm) and hand length of 181.58 mm (SD 17.71 mm), and the RFA group had an average hand breadth of 83.52 mm (SD 5.64 mm) and hand length of 184.80 mm (SD 13.42 mm). Hand sizes for both the Healthy and RFA groups ranged from at least 25th to 90th percentile based on both hand breadth and hand length for both males and females (Greiner, 1991). Informed consent was obtained from each participant under the direction of Michigan State University's Institutional Review Board (IRB # 09-179).

2.2. WFS modeling

The framework for evaluating and modeling hand capabilities was the WFS model, previously developed by the authors (Leitkam et al., 2013). The WFS model was a 3D volume representing points that were reachable by each fingertip pad in space and weighted by three parameters that addressed levels of functionality for the fingertips.

1. The *Redundancy* weighting represented the kinematic redundancy of the hand as measured by the relative number of possible finger postures that allow a fingertip to reach each point.
2. The *Orientation* weighting represented the angular range of possible orientations that the fingertip could assume at each point.
3. The *range of force application directions,* or *FAD* weighting, represented the angular range of possible directions the fingertip could apply forces at each point.

2.3. Development of individual WFS models

The WFS model for each individual was developed by modeling the hand as a system of 16 different rigid bodies, corresponding to each of the phalanges of the hand, the first metacarpal and the palm. The rigid bodies were connected with 15 different joints, capable of producing 20 unique angular rotations, corresponding to flexions/extensions and abductions/adductions of the fingers, and flexions/extensions and rotations of the thumb about the carpometacarpal joint. The lengths of each of the bodies were measured for every individual using a caliper. The ROM for each angular rotation was determined using motion capture measurements. Detailed descriptions of the specific motions, hand measurements and targeting protocol can be found in previously published work on the development of the WFS model (Leitkam and Bush, 2015; Leitkam et al., 2013).

The rigid body model of the hand was then used to calculate equations for the fingertip position and orientation for each finger with respect to the palm as functions of the joint angles using the Denavit–Hartenberg convention. Fingertip positions, orientation vectors, and possible force application direction vectors were calculated for all joint angle combinations feasible within each finger's ROMs. The fingertip position was defined as the center of the palmar surface of the distal phalange, halfway between the DIP joint and the fingertip along the centerline of the finger. The orientation was defined with unit vectors normal to the center of the palmar surface of the distal phalange. The FADs were unit vectors originating at the center of the palmar surface and pointing in the direction of the gradient of motion of each of the flexion joints of the finger. By rounding the position coordinates of the vectors for each finger posture to the nearest 2.5 mm value, the calculated fingertip positions, orientations, and FADs were organized to a 3D grid of points with a mesh size of 2.5 mm.

2.3.1. Redundancy weighting

The grid was assigned a color mapping related to the number of unique finger postures that resulted in the fingertip pad reaching each grid location. A larger value indicated a higher level of redundancy in finger postures capable of positioning the finger pad at a particular point.

2.3.2. Orientation weighting

The *Orientation* weighting parameter was based on the range of fingertip orientation vectors collected at each mesh point. At each reachable mesh point in the WFS the two orientation vectors that formed the limits of the angular range were identified and the angle between the limiting vectors was calculated. A larger orientation angle indicated a higher level of functional capacity of the finger to orient the fingertip within the WFS at that location.

2.3.3. Range of FADs

The *Range of FADs* was calculated to be a value that represented the maximum angular range of FAD vectors accumulated at each grid location. Each FAD corresponded to a flexion movement of one of the joints of the finger (MCP, PIP, and DIP) and represented the direction in which a grasping or button actuation force could be generated at the fingertip pad. A larger FAD angle indicated a higher range of FADs and that was considered a larger functional ability as forces could be applied in a greater variety of directions (Fig. 1).

2.4. Development of group WFS models

Group WFS models were calculated by merging the WFS models from the individuals in the Healthy and RFA groups and represented the number of the participants out of each group that could reach the same points in 3D space. The individual models were merged by first determining the average position of each MCP joint of the individuals in each group. Then the WFS models for each finger were translated in the radial–ulnar and proximal–distal directions such that the individual MCP location was moved