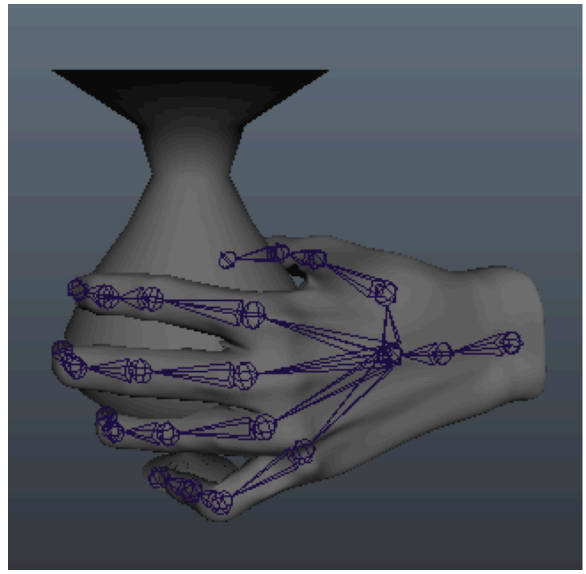
Abstract:

The objective of the proposed method is to create a design environment in which a user can receive real time feedback about the ergonomic qualities of the object they are creating. Within this tool, the user models their object, using a surface of revolution based on a Bezier curve, and positions a model of a human hand into a grasping pose on the object. The use of a Bezier curve allows the method to make simplifying assumptions about contact intersections and tangent planes at contact points, which are then used to solve the force optimization problem. The solution to this force optimization problem indicates the amount of force necessary for the object to resist external forces, such as gravity or additional forces indicated by the user. This information can then be use to infer the strain on joints of the hand, to determine how strenuous the grasp is.



1. Introduction

With over 2 million Canadians suffering from repetitive strain injury (RSI) severe enough to limit their daily activity [1], incorporating ergonomic principles into the design of objects is increasingly crucial. Physical ergonomic design principles are fundamentally concerned about designing an object in such a way that, the designed object is easy to use and adaptable, while minimizing potential injury during user interactions. These design principles are particularly important for objects that must be repetitively gripped, as the continual repetition of an interaction with an object can readily lead to a repetitive strain injury. While RSI can be addressed by changing the interaction, either by gripping the object in a different manner or reducing the amount of repetitious interactions, it can also be minimized through ergonomic design of the object itself. In particular, the object could be designed to better fit the anatomy of the intended user, allowing for a better distribution of grasping forces and less joint strain during a particular interaction. Therefore, a method for designing objects that respect these ergonomic principles and can, in real time, determine the interaction of forces required to grasp an object subject to a particular set of forces is proposed in this paper. The proposed method allows the user to design an object as a surface of revolution generated from a design curve, position a gripper that will interact with the object and indicate additional forces that might act upon the object in the environment. The method uses this information to determine the minimal force necessary at each contact point of the gripper on the object, such that the object is grasped stably. Furthermore, the method indicates to the user how this force is distributed on the hand, indicating which joints may be required to endure a potentially hazardous amount of strain. The user can then quickly redesign the object, or reposition the gripper to see how the distribution of force and joint strain changes, helping them to design a more ergonomic object.

2. Related Work

In general, much of the existing research of ergonomic grasping has focused on empirical studies or analysis derived from simulations of physical interactions governed by simplified physical laws [2]. Empirical based studies have often focused on organizing various grasp strategies and grasp poses into a fundamental set of grasp taxonomy. These grasp taxonomies are typically based on observations on how humans typically attempt to grasp different types of objects (prehensile movements). Taylor and Schwarz [3], who summarized the work of Schlesinger [4], proposed six basic grasp prehension patterns (figure 1): cylindrical, fingertip, hook, palmer, spherical, and lateral. Though there are likely infinite varieties of possible prehension patterns, these 6 patterns describe a satisfactory basis for grasp classification and observed to be naturally assumed by

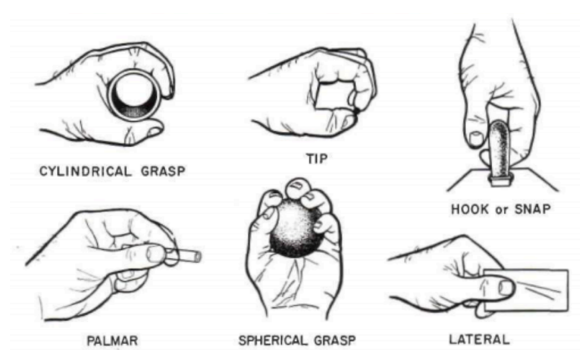


Figure 1. The 6 types of prehension grasp (adapted from Taylor and Schwarz [3])

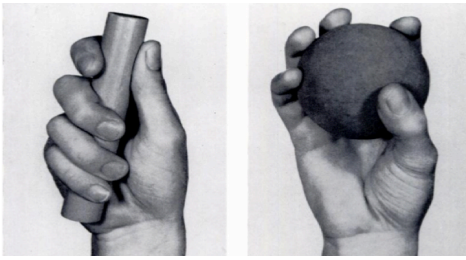


Figure 2: Power and precision grip (adapted from Napier [5])

individuals when picking up and holding common objects. In particular, these prehension patterns appear to be chosen based on the shape of the object the hand is about to interact with. However, while these prehension grasps can adequately describe how humans begin a grasp, or hold an object at equilibrium, they are less useful for describing how the grasp functions during a given task with an object. For instance, the hand will likely assume a different grasp pose, in order to impart and resist a different set of forces, when screwing in a light bulb as oppose to holding it at equilibrium. Thus, Napier [5] devised two categories of grasp types: power grasps and precision grasps (figure 2). Power grasp are characterized by grasps that utilize large areas of contact that distribute force, but where any single point contact part is unable to impart motion on the object. By contrast, precision grasps utilize small areas of contact, which allows each digit of the hand to finely control the motion of the object. Napier then suggests a hierarchy of grasps within the power and precision grasps, where each grasp in the hierarchy is suited to a particular combination of task and object geometry. However the taxonomy proposed by Napier is limited in that it cannot exhaustively account for every task and object geometry combination. Furthermore, the taxonomy does not take into account individual differences in hand size, shape, and strength, which can vary drastically with age and medical history [6]. However, these grasp taxonomies can be used to formulate an initialize a grasp pose, which is then altered and positioned by the user to fit the specific object geometry and interaction that is relevant to their design process.

As oppose to taxonomy schemes, a number of analytical methods that predict the stability and comfort of grasps based on simulations have been developed. Generally, these simulations use idealized models of physical laws to simplify calculations, particularly with regards to contact elasticity and contact friction (see section 4). Many of these simulations have been focused on grasp planning strategies for robotic systems, determining how a robotic gripper should attempt to grasp an object. While the focus of these studies within robotics have not been focused on ergonomics or comfort, they provide valuable insight into how to efficiently determine if a grasp is stable as well as how to compute the minimal forces needed to maintain the grasp. Often these studies focus on force closure, the ability for the grasp to resist an arbitrary worst-case wrench force upon the object being grasped. Intuitively, a metric based on this force closure compares how much force must be exerted at the contact points in order to resist an arbitrary external wrench. To quantify this metric, the concept of wrench spaces, in particular the grasp wrench space (GWS) - the set of all wrenches that can be applied to the object through the contact points, can be used. A common method of evaluating the GWS is to determine a convex hull over the discretized boundary of friction cones at the contact points. Then, the displacement of the hull by an external wrench is computed, where a greater displacement of the boundaries of the hull from the origin indicates a less stable grasp [7,8]. However, the choice of discretization, meant to avoid a nonlinear friction model, can introduce a substantial amount of error. Additionally, while the metric provides insight into stability against a worst-case external wrench, it does not necessarily provide insight on how well the grasp functions against external wrenches encountered during the task. Pollard [9] defined another common metric, in which the fitness of the grasp is based on comparing the GWS to the task wrench space (TWS). However, this method assumed a frictionless point contact model, and the choice of TWS can be difficult to determine. Recent work has focused on determining the minimal set of forces that must be imparted at contact points to counteract a specific set of external wrenches and hold the object at equilibrium. This problem is often referred to as the force optimization problem (FOP). Generally, the major computational difficulty is a result of determining the tangential frictional forces at contact point, which is bound by a nonlinear term. Buss, Hashimoto and Moore [10] showed that FOP could be formulated as a convex optimization problem, where the friction constraints could be described as second order cone constraints. Further work improved on this formulization, creating more compact constraints [11] or formulating the optimization as a dual problem [12]. However, these studies have generally been directed towards objects with static geometry. Additionally, these studies also do not consider the ergonomics of the grasp beyond basic feasibility with respect to the capabilities of the robotic gripper.

Recent work has attempted to pair these grasp stability analysis methods with more realistic models of hands in order to understand the ergonomics of grasps applied to various objects. Y. Endo et al [13] developed a method to find an ergonomic grasp pose using a realistic model of a human hand, derived from MRI analysis

[14,15]. Y. Endo et al's method divided digits of the hand into one active and three passive fingers, where the user indicates where the palm and active fingers should intersect the object. The system then automatically formulates a rough grasp pose that uses these contact points by translating the hand, and rotating the joints of the digits onto the object in order according to a predetermined task. The degrees of freedom and joint rotation limits were determined from the work of Lee and Kunii [16]. Grasp quality was the determined using a convex hull method, similar to [7,8]. The ergonomic quality of the grasp is then determined by comparing the first M principal components of the joint matrix to user study tested grasp poses, which were rated for comfort by human participants. However this study, and additional work by Y. Endo et al [17], focused on automatic generation of ergonomic poses with minimal user input and static object geometry. Finally Pitarch[18] developed a method focused on designing aesthetically please PET bottles, while also considering the ability of the bottle to be easily grasped. In this study, grasp stability was determined by computing the moment forces at each contact point, factoring in different amount of liquid within the bottle. In this work, the design of the object is automatically generated from descriptive key words by the user and from indicated target cross sectional values.

3. Advantages of the Bezier Curve and Surface of Revolution for Object Modeling

The proposed method makes use of a surface of revolution generated by revolving a profile curve, made up of conjoined cubic Bezier curves, around the y-axis. Furthermore, the profile curve is constrained to be planar and non-self intersecting. By choosing a surface of revolution based on a Bezier curve, the method is able to greatly optimize the computation of intersections, of the object and hand, and computations of tangent planes at intersection points.

By construction of the surface of revolution, the radius of the surface at any point along its height is equal to the width of the profile curve at that same height. Thus, to compute intersection points, the width of the profile curve is sampled at uniformly spaced points along the height of the object. The value of the width is then stored in a hash map that maps height values along the y-axis to radial values of the surface of revolution.

Once the hash map is computed, the center of mass (COM) of the object can be computed as a weighted average. Since the object is uniformly rotated around the y-axis, the center of mass itself must lie on the y-axis and can be estimated as follows:

$$w_i = hash(y_i)$$

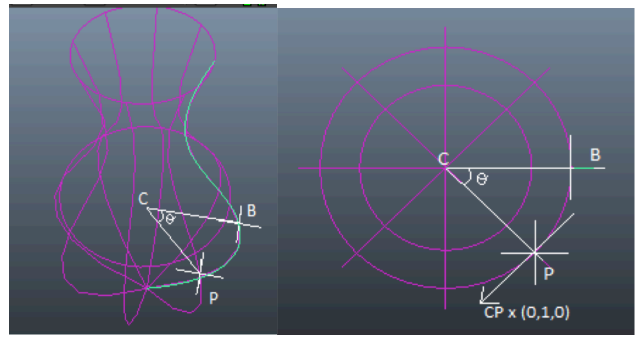


Figure 3: The surface of revolution shown in purple, the profile Bezier curve in green, B the point on the profile Bezier curve, P the intersection point on the surface, and C the point at the same height on the y-axis. Shown in perspective (left), and the xz-plane (right)

$$COM_y = \frac{\sum w_i y_i}{n}$$

Where y_i is uniformly sampled along the height of the object, w_i is the corresponding width for the sampled height and n is the number of curve samples.

To compute intersections, the method examines each vertex in the model of the hand and indexes into the hash map based on the height of the vertex point. Then, an intersection occurs if the vertex lies within the hash map's corresponding radius:

$$r_i = hash(p_y)$$
$$r_i \geq \sqrt{{p_x}^2 + {p_z}^2}$$

Depending on how detailed the hand model is, there many be many adjacent intersections. To reduce redundant calculations, the location of each intersection is averaged together with other nearby intersection.

For each point in the reduced set of intersection points, a tangent plane is computed, to determine tangential gripping forces later in the method. As the profile curve is a Bezier curve, a tangent vector for any point on the Bezier curve can be found using the formula:

$$B'(t) = 3(1-t)^2(P_1 - P_0) + 6(1-t)t(P_1 - P_0) + 3(t)^2(P_3 - P_2)$$

By construction of the surface of revolution, each point **P** on the surface has a corresponding point **B** on the Bezier curve that differs only by a rotation **θ** around the y-axis (see figure 3). Letting **C** be a point on the y-axis at the same height as B and P, θ can be computed as the angle between CB and CP. Similarly, the tangent vector at point P is the same as the tangent vector at point B on the Bezier curve rotated by θ around the y-axis.

Similar to the surface of revolution radii sampling described previously, a second hash map can be constructed that maps height values along the y-axis to a corresponding tangent vector of the Bezier curve. Thus, the first tangent vector at point P can be constructed by indexing into the tangent hash map at P_y, and then

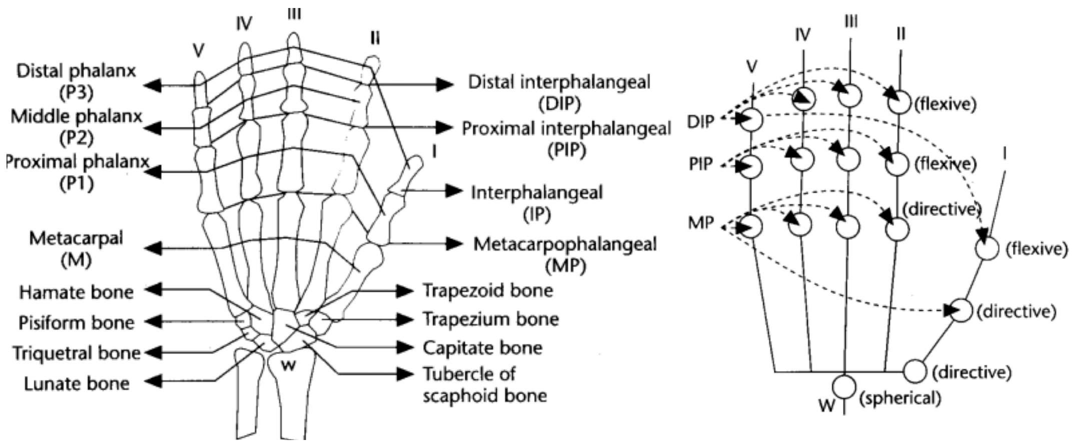


Figure 4: a diagram of the skeletal structure of the hand (left), degrees of freedom of the joints in the model of the hand (right) (adapted from J Lee, and TL Kunii [16])

rotating the corresponding tangent vector by θ around the y-axis to correspond to point P. The second tangent vector is obtained through the observation that the surface of revolution can be viewed as a circle for a slice in the xz plane at a given point along the y-axis. Then, the second tangent vector can be generated as the cross product of CP and (0,1,0) as seen in figure 2. These two tangent vectors are then used for the tangent plane for the intersection point to compute tangential forces exerted at the point.

4. Force Optimization Problem

In formalizing the FOP, the model of friction used has a strong effect on the difficulty of the problem, particularly if the friction is defined through nonlinear constraints. In general, most formalizations of the FOP use one of the following models of friction: (a) frictionless point contact (FPC), (b) point contact with friction (PCWF), or (c) soft finger contact (SFC). The proposed method will focus on the PCWF model of contact, where the grasper is considered as a rigid body that transmits force through point of contacts on the surface of the object. For a contact point p_i, the force f exerted on the object must follow Coulomb's law and can be formulated as:

$$f_i = \{c_{i,1},\ c_{i,2},\ c_{i,3}\}$$

$$\sqrt{{c_{i,2}}^2 + {c_{i,3}}^2} \le \mu_i c_{i,1}\,, \qquad c_{i,1} > 0$$

Where $c_{i,1}$ is the normal force component projected into the object, $c_{i,2}$ and $c_{i,3}$ are the tangential force components and μ_i denotes the friction coefficient at p_i. The equilibrium constraints, which ensure the object is held stable, can be represented as follows. Let Q_i be the transformation matrix that transforms forces in the local coordinate system at a contact point p_i. Then, the force exerted at p_i in the global coordinate system is

$$Q_1 f_1 + Q_2 f_2 + \cdots + Q_n f_n + f_{ext} = 0$$

Where f_{ext} is the total external force, in the global coordinate system, acting on the object.

Next, under a rigid body assumption, the torque applied to the object at a contact point p_i is given by:

$$p_i \otimes Q_i f_i$$

The torque equilibrium constraint can be represented as:

$$p_1 \otimes Q_1 f_1 + p_2 \otimes Q_2 f_2 + \cdots p_n \otimes Q_n f_n + \tau = 0$$

Where τ represents the total external torque, in the global coordinate system, that acts on the object.

Then, we can formulate the force optimization problem as:

Minimize: $\sum f_i$

Subject to: $\sqrt{{c_{i,2}}^2 + {c_{i,3}}^2} \le \mu_i c_{i,1}$ (1)

$Q_1 f_1 + \cdots + Q_n f_n + f_{ext} = 0$ (2)

$p_1 \otimes Q_1 f_1 + \cdots p_n \otimes Q_n f_n + \tau = 0$ (3)

However, as shown in [10-12], the friction cone constraint (1) can be rewritten as:

$$\begin{bmatrix} \mu_i c_{i,1} & 0 & c_{i,2} \\ 0 & \mu_i c_{i,1} & c_{i,3} \\ c_{i,2} & c_{i,3} & \mu_i c_{i,1} \end{bmatrix} \succcurlyeq 0$$

Which leads to the standard SDP formulation of the FOP.

5. Hand model and Joint Comfort

The model of the hand is based on the findings of J Lee, and TL Kunii [16]. Each joint in the hand has a specific degree of freedom associated with it (see figure 4): a single DOF flexion movement joint, a two DOF directive movement joint, and a three DOF spherical movement joint.

To compute the strain a particular grasping force imposes on the joints of the hand, contact points are assigned to the closest digit or the palm. Then, the force exerted at each contact point assigned to the digit can be summed in order to compute the percentage of total force exerted on the object that is contributed by the specific. This information is conveyed to the user as a color map, where the intensity of the color corresponds to the percentage of force exerted by the digit. Further, the angle of each joint in the hand is computed as the joint's local rotation from the flat resting pose of the hand. The more extreme the angle of the joint is, the higher the intensity of the color map in the vicinity of the joint is scaled. This color map allows the user to see the concentration of strain on the joints as a result of the grasping pose and object design.

6. Conclusion and future work

The proposed method makes several sacrifices in order to improve calculations. In particular, the object is forced to be uniform around the y-axis. However, the method could be redesigned to allow the object to be formed from several attached surfaces of revolution. In this case, the center of mass could be computed separately for each component surface of revolution and then averaged. Similarly the points of contact could be evaluated on each surface of revolution and the resultant motion of the object determined under the assumption that the entire object is a single rigid body. Other future improvements could involve a more sophisticated joint model that respects the joint dependencies outlined in J Lee, and TL Kunii [16] (e.g the rotation of DIP joint causes a rotation in the adjacent PIP joint).

Thus, the constraints imposed on the object's design allow for assumptions that facilitate rapid calculations of intersections and contact tangent planes. These calculations are then used to solve the FOP, which can then be used to give the designer feedback on the effectiveness of the objects design with respect to the specific grasping pose. Thus, the proposed method presents an effective way for a designer to receive feedback about the ergonomic qualities of their design in real time.

7. References:

1. F. Breslin et al, "The demographic and contextual correlates of work‐related repetitive strain injuries among Canadian men and women." *American journal of industrial medicine* 56.10 (2013): 1180-1189.
2. M. Cutkosky and R. Howe. "Human grasp choice and robotic grasp analysis." *Dextrous robot hands*. Springer New York, 1990. 5-31.
3. C. Taylor, and R. Schwarz. "The anatomy and mechanics of the human hand." *Artificial limbs* 2.2 (1955): 22-35.
4. G Schlesinger, Der mechanische Aufbau der kunstlichen Glieder in *Ersatzglieder und Arbeitshilfen,* Springer, Berlin, 1919.
5. J. Napier, "The prehensile movements of the human hand." *Journal of bone and joint surgery* 38.4 (1956): 902-913.
6. M Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks." *Robotics and Automation, IEEE Transactions on* 5.3 (1989): 269-279.
7. C. Ferrari and J. Canny, "Planning optimal grasps." *Robotics and Automation, 1992. Proceedings., 1992 IEEE International Conference on*. IEEE, 1992.
8. A. Miller et al, "Automatic grasp planning using shape primitives."*Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference on*. Vol. 2. IEEE, 2003.
9. N. Pollard, "Synthesizing grasps from generalized prototypes." *Robotics and Automation, 1996. Proceeding, 1996 IEEE International Conference on*. Vol. 3. IEEE, 1996.
10. M. Buss, H. Hashimoto, and J. Moore. "Dextrous hand grasping force optimization." *Robotics and Automation, IEEE Transactions on* 12.3 (1996): 406-418.
11. L. Han, J. Trinkle, and Z. Li, "Grasp analysis as linear matrix inequality problems." *Robotics and Automation, IEEE Transactions on* 16.6 (2000): 663-674.
12. S. Boyd, and B. Wegbreit, "Fast computation of optimal contact forces." *Robotics, IEEE Transactions on* 23.6 (2007): 1117-1132.
13. Y Endo, et al. "Virtual grasping assessment using 3D digital hand model."*Annual Applied Ergonomics Conference: Celebrating the Past-Shaping the Future*. 2007.
14. Y. Shimizu et al, "Constructing MRI-based 3D precise human hand models for product ergonomic assessments." *한국 CAD/CAM 학회 논문집* (2010): 837-844.
15. N. Miyata et al, "Finger joint kinematics from MR images." *Intelligent Robots and Systems, 2005.(IROS 2005). 2005 IEEE/RSJ International Conference on*. IEEE, 2005.
16. J Lee, and TL Kunii. "Model-based analysis of hand posture."*Computer Graphics and Applications, IEEE* 15.5 (1995): 77-86.
17. Y. Endo, et al. *Optimization-based grasp posture generation method of digital hand for virtual ergonomics assessment*. No. 2008-01-1902. SAE Technical Paper, 2008.
18. Widiyati, Khusnun, and Hideki Aoyama. "Gripping Stability to Assess Aesthetical Shape: A PET Bottle Case Study." *Advanced Materials Research*566 (2012): 454-461.
19. E Pitarch, "Virtual human hand: Grasping strategy and simulation." (2008).