Full Length Article

A soft-contact model for computing safety margins in human prehension

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A B S T R A C T

The soft human digit tip forms contact with grasped objects over a finite area and applies a moment about an axis normal to the area. These moments are important for ensuring stability during precision grasping. However, the contribution of these moments to grasp stability is rarely investigated in prehension studies. The more popular hard-contact model assumes that the digits exert a force vector but no free moment on the grasped object. Many sensorimotor studies use this model and show that humans estimate friction coefficients to scale the normal force to grasp objects stably, i.e. the smoother the surface, the tighter the grasp. The difference between the applied normal force and the minimal normal force needed to prevent slipping is called safety margin and this index is widely used as a measure of grasp planning. Here, we define and quantify safety margin using a more realistic contact model that allows digits to apply both forces and moments. Specifically, we adapt a soft-contact model from robotics and demonstrate that the safety margin thus computed is a more accurate and robust index of grasp planning than its hard-contact variant. Previously, we have used the soft-contact model to propose two indices of grasp planning that show how humans account for the shape and inertial properties of an object. A soft-contact based safety margin offers complementary insights by quantifying how humans may account for surface properties of the object and skin tissue during grasp planning and execution.

1. Introduction

In the sensorimotor control literature, safety margin, the normalized difference between the applied grip force and the minimal grip force to prevent slipping (Hermsdörfer, Hagl, Nowak, & Marquardt, 2003; Westling & Johansson, 1984), is frequently used to quantify grasp planning. The minimal grip force is prescribed by the object's weight and the friction coefficient between the glabrous skin of the hand and the grasped object. Humans scale grip forces by estimating the friction coefficient between the digits and the grasped object: the smoother the surface, the larger the applied grip force (reviewed in Flanagan & Johansson, 2010).

This analytical framework is based on the hard-contact model which assumes that digits can apply a three-dimensional force vector but no free moment to the object. The hard-contact model presumes that a grasped object will not slip from the fingers as long as the force vector at each digit-object contact is in the interior of a friction cone (defined in the 3D space of contact forces). However, this model does not capture the richness of the human prehension repertoire (Singh & Ambike, 2015). The dynamic interactions between the human digits and grasped objects are more realistically modeled as soft contacts in which the digits apply a three-dimensional force vector to the object and a free moment about the normal to the contact surface. Here, we propose a soft contact

based safety margin and demonstrate how it can be used to quantify grasp planning and stability.

In his pioneering work, Heinrich Hertz described the geometry and stress distribution of two elastic bodies in contact and exerting only a normal force on each other (Hertz, 1882). His model was further developed and validated for non-linear material properties, including human fingers (Kao & Cutkosky, 1992; Li & Kao, 2001; Xydas & Kao, 1999). These authors added the Coulomb friction model and allowed a 3D force vector and a moment about the contact-area normal to be applied at the applied contact site. These contact characteristics, which define a soft contact (Murray, Li, & Sastry, 1994), constitute a realistic model to study human digit-object interactions. It has been widely used in robotics (Yoshikawa, 2010), but to the best of our knowledge has only been introduced in a few studies of human prehension (Kinoshita, Bäckström, Flanagan, & Johansson, 1997; Shim, Latash, & Zatsiorsky, 2005; Singh & Ambike, 2015). Kinoshita et al.'s model of safety margin for soft contacts is data driven and does not provide a mechanistic framework to quantify grasp planning. Furthermore, their model is only applicable to a specific experimental design where the applied external loads are assumed to be in one plane, and consequently, their results are not generalizable to an object grasped in an arbitrary orientation.

Here, we review the hard- and soft-contact models in Section 2. We propose a soft contact based safety margin as a complementary measure of grasp mechanics that reflects how humans execute grasps by accounting for surface friction (Adams et al., 2013; Cadoret & Smith, 1996) and local physiological changes. Since our model is based on mechanics, it is not constrained by the limitations of Kinoshita et al.'s model (Kinoshita et al., 1997) and can be used to study grasps in any configuration. We also propose a mathematical framework for the implementation of a soft contact based safety margin for human prehension. In Section 3, we reinterpret data from a previous study (Singh, Zatsiorsky, & Latash, 2013) to illustrate the utility of the proposed metric. Finally, in Section 4, we discuss our findings and conclude by discussing the potential applications and benefits of a soft-contact model.

2. Methods

2.1. Contact models

2.1.1. A hard-contact friction model and safety margin

For hard-contact models, the friction cone determines the ratio of tangential to normal forces that can be exerted on the object without slipping (Fig. 1A). The cone surface is a boundary, and the contact force vector must lie within this boundary for a stable contact to occur (i.e., contact without slip). If Coulomb's law of friction is employed, the friction cone, or, more generally, the Friction Limit Surface (FLS), is given by:

$$\frac{(x_F)^2 + (y_F)^2}{(\mu_s)^2} = (z_F)^2 \tag{1}$$

where x_F, y_F and z_F are variables for the two orthogonal tangential forces and the normal force, respectively (see Fig. 1A). We then define the applied force vector, $\mathbf{W_{applied}} = [\ F^X, F^Y, F^Z]$. That is, we view the subject's actual finger forces F^X, F^Y, and F^Z as specific values plotted along the x_F, y_F and z_F axes, respectively. The vector $\mathbf{W_{applied}}$ is called the slip vector, consistent with the robotics literature (Kao & Cutkosky, 1992). The key idea is that the slip vector is constrained to lie within the FLS to prevent slipping. The cone surface (FLS) in Fig. 1A represents the condition in which the normal force F^Z is exactly sufficient to generate sufficient tangential force to balance the inertial load imposed by the object. The slip vector in Fig. 1A is a loading at a finger-object contact. The vector is in the interior of the FLS, so there is no slip. Furthermore, the tangential force components of the vector are determined by the friction coefficient and the object-induced inertial loads. However, the normal force is applied by the subject, and it determines the location of the slip vector relative to the FLS. In typical static grasping experiments that implement planar analyses, the tangential component of the applied force vector ($\|F^{X,Y}\| = \sqrt{(F^x)^2 + (F^y)^2}$), is determined by the weight of the object alone, and the other tangential component orthogonal to the weight vector is 0 (i.e. either F^x or $F^Y = 0$). However, $F^{X,Y}$ for a grasped glass that is being transported from a table to the mouth for a sip would have two non-zero tangential force components.

This implies that, in planar grasps, the minimum normal force required to avoid slip is $F^Z_{min} = \|F^{X,Y}\|/\mu_S$. Then, Safety Margin (SM)
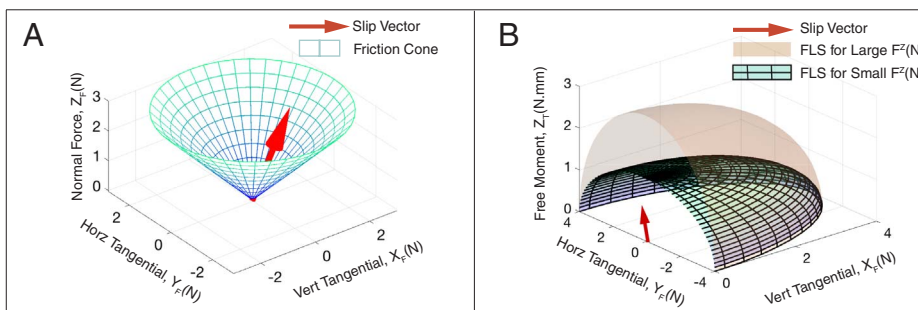

Fig. 1. Friction models. A) The hard-contact friction model; the applied slip vector ($\mathbf{W_{applied}} = [F^X, F^Y, F^Z]$) is constrained to lie within the boundaries of the friction limit surface (cone). B) The soft-contact model; the slip vector ($\mathbf{W_{applied}} = [F^X, F^Y, F^Z]$) shown in red is constrained to lie within the friction limit surface (ellipse). The volume encompassed by FLS is dictated by the applied normal force.