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Short communication

# A soft-contact and wrench based approach to study grasp planning and execution

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ABSTRACT

Grasping research in robotics has made remarkable progress in the last three decades and sophisticated computational tools are now available for planning robotic grasping in complex environments. However, studying the neural control of prehension in humans is more complex than studying robotic grasping. The elaborate musculoskeletal geometries and complex neural inputs to the hand facilitate a symphonic interplay of power and precision that allows humans to grasp fragile objects in a stable way without either crushing or dropping them. Most prehension studies have focused on a planar simplification of prehension since planar analyses render the complex problem of prehension tractable with few variables. The caveat is that planar simplification allows researchers to ask only a limited set of questions. In fact, one of the problems with extending prehension studies to three dimensions is the lack of analytical tools for quantifying features of spatial prehension. The current paper provides a theoretical adaptation and a step-by-step implementation of a widely used soft-contact wrench model for spatial human prehension. We propose two indices, *grasp caliber* and *grasp intensity*, to quantitatively relate digit placement and digit forces to grasp stability. Grasp caliber is the smallest singular value of the grasp matrix and it indicates the proximity of the current grasp configuration to instability. Grasp intensity is the magnitude of the excessive wrench applied by the digits to counter perturbations. Apart from quantifying stability of spatial grasps, these indices can also be applied to investigate sensory-motor coupling and the role of perception in grasp planning.



## 1. Introduction

Wrench models are widely used in robotics to study grasping. A variant of these models, which represents human digits as hard contacts, has been adapted for studying human prehension (León et al., 2012; Wells and Greig, 2001). However, human digits are soft contacts that apply a four-component *wrench* (three force components and a *free moment* normal to the contact surface) on objects (Mason and Salisbury, 1985). Soft-contact models for human prehension have been proposed (Li and Kao, 2001; Xydas and Kao, 1999) but to the best of our knowledge, there are no papers that provide a methodology to implement a wrench based, three-dimensional (3D), soft-contact model for studying spatial prehension.

One compelling motive for building a soft-contact model is that hard contacts cannot model certain grasp conditions. For example, with hard contacts, static restraint of an object with two opposing digits is impossible. Imagine grasping a golf ball with the thumb and the index finger with cone-shaped thimbles glued to the fingertips (Fig. 1A). While the thimble can apply forces in arbitrary directions, it cannot apply a free moment (a feature specific to soft contacts). This grasp cannot influence the rotation of the ball about the *Z*-axis. This is nontrivial because each thimble applies a three-dimensional wrench and the two thimbles together apply a six dimensional wrench that should be able to constrain the six kinematic degrees of freedom of the ball. However, the *grasp matrix* (defined below) for this two-digit contact is rank deficient (rank=5), and hence the grasp is not *force-closure*[1] and therefore unstable.

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[1] Force-closure grasps are grasps in which the fingers can resist arbitrary external wrenches.

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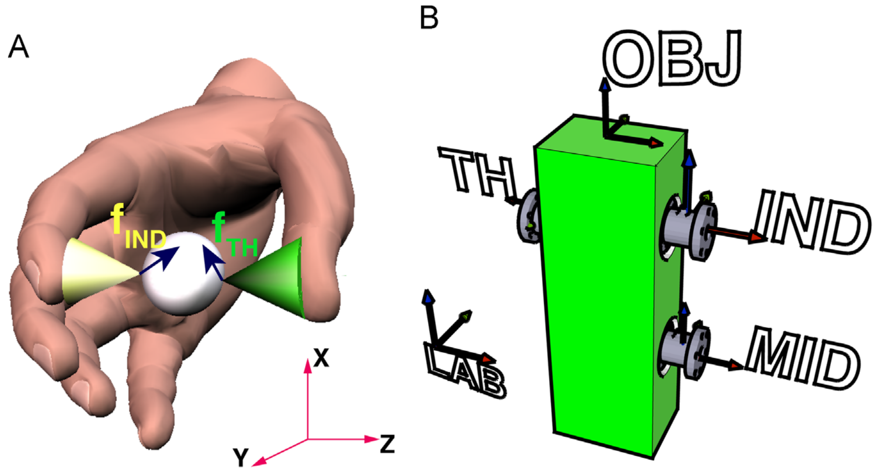


**Fig. 1.** (A) The thimbles are glued to the glabrous skin of the digits, and they only allow forces to be exerted on the balls. The arrows show the direction and magnitude of the wrench vectors ($f_{TH}$ and $F_{IND}$). If the golf ball is spun around the *Z*-axis, it would not be possible to resist the spin and bring the ball to a rotational equilibrium. (B) A schematic of a setup for a tripod grasp. Local frames are affixed to the center of the three force transducers (TH, IND and MID). A kinematic sensor provides spatial kinematic information of a reference frame attached to the object (OBJ) with respect to a fixed laboratory based reference frame (LAB).

Grasp matrices have been previously used to study grasp stability in robotic grasps (Howard and Kumar, 1996). In this paper, we obtain two indices (*grasp caliber* and *grasp intensity*) from the grasp matrix to quantify the effects of grasp planning (choice of digit placement on the object) and execution (choice of digit forces) on grasp stability in humans. We will show that computing the grasp matrices in the appropriate coordinate frame is critical to studying grasp stability. The purpose of the current paper is to provide a step-by-step procedure for computing grasp matrices in different coordinate frames and to compute *grasp caliber* and *grasp intensity* to quantify grasp stability.

## 2. Methods

The wrench applied by the fingertips is related to the external wrench on the grasped object ($\mathbf{w}$) by the *grasp matrix*, $\mathbf{G}$:

$$-\mathbf{w} = [\mathbf{G}]\mathbf{f_C} \tag{1}$$

The external wrench $\mathbf{w} \in R^p$ ($p$=3 for planar and $p$=6 for spatial analysis) is prescribed in the laboratory frame. $\mathbf{f_C} \in R^m (m = m_1 + m_2 + \ldots + m_k)$ is the concatenated *wrench intensity vector* applied by the digits and specified in local frames at the point of wrench application (see Section 2.1 ). For digit k, $m_k$ is the dimensionality of its wrench vector, and it depends on the type of contact model (3 for hard-contact and 4 for soft-contact models). The grasp matrix $[\mathbf{G}] \in R^{p \times m}$ maps the fingertip wrenches to a laboratory-based reference frame. In the case of a three-digit tripod grasp with soft contacts (Fig. 1B), $\mathbf{f_C}$ is a 12-dimensional vector ($[f_x, f_y, f_z, m_z] \times 3$ digits; $f_x$=force along the $x$ axis, $m_z$=moment about the $z$ axis, and so on), and $[\mathbf{G}] \in R^{6\times 12}$ .

The concatenated *wrench intensity vector* (which we henceforth call '*wrench*') is written as:

$$\mathbf{f_C} = (\mathbf{f}_{\mathbf{C}_{TH}}, \mathbf{f}_{\mathbf{C}_{IND}}, \mathbf{f}_{\mathbf{C}_{MID}}) \tag{2}$$

where TH stands for thumb, IND for index and MID for middle finger.

### 2.1. Computing the wrench for a soft-contact model

We first obtain the wrench applied by a digit, $\mathbf{f}_{\mathbf{C}_k}$ (k=TH, IND or MID), from the output of a 6D transducer. For a soft-contact model, $\mathbf{f}_{\mathbf{C}_k}$ is $\left(f_x, f_y, f_z, m_z\right)$, with the $z$-axis perpendicular to the sensor surface. Suppose that the instantaneous force reading is $\mathbf{p_k} = (p_x, p_y, p_z)$ in a reference frame at the center of the sensor and $\mathbf{q_k} = (q_x, q_y, q_z)$ is the moment about the same coordinate axes (Fig. 2A). For a hard-contact model, $\mathbf{f} = \mathbf{p}$, $\mathbf{m} = \mathbf{0}$ and there is a closed-form solution to the problem (Bicchi et al., 1993). For a soft-contact model, contact between the digit and the sensor surface occurs over a finite area but a unique *contact centroid* can be defined for a non-concave sensor surface. Then the contact problem for a soft-contact wrench can be defined as follows: For a given measurement ($\mathbf{p_k}$, $\mathbf{q_k}$), determine the location of the point of wrench application, $\mathbf{PWA_k}$, and the related wrench $\mathbf{f}_{\mathbf{C}_k} = (\mathbf{f_k}, \mathbf{m_k})$ where $\mathbf{m_k} = (0,0,m_z)$. For flat sensor surfaces, this reduces to computing the center-of-pressure on a force platform (Zatsiorsky, 2002).

### 2.2. Wrench basis and friction cones

Grasp matrices are constructed using a *wrench basis*, $[\mathbf{B}_{C_k}] \in R^{p \times m_k}$ and a *friction cone*, FC (Murray et al., 1994). The dimension of the wrench basis depends on the contact model.

For a hard-contact model with friction,

$$[\mathbf{B}_{C_k}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3a}$$

For a soft-contact model,

$$[\mathbf{B}_{C_k}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3b}$$

The 6D contact wrench that is applied by a digit on the object is:

$$\mathbf{W}_{\mathbf{C}_k} = \mathbf{B}_{\mathbf{C}_k}\mathbf{f}_{\mathbf{C}_k} \text{ where } \mathbf{f}_{\mathbf{C}_k} \in \text{FC} \tag{4}$$

That is, the set of wrenches that can be applied at a contact must lie within the friction-cone (FC) centered about the surface normal at the PWA. For a hard-contact model with friction,

$$\text{FC} = \mathbf{f} \in R^3 : \sqrt{f_x^2 + f_y^2} \le \mu_z f_z, f_z \ge 0 \tag{5a}$$