Predicting Grasp Inertia with a Geometric Model

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Abstract

Controlling finger impedance is critical for successful grasping. Understanding how humans achieve this is of great interest for learning about human motor control, as well as for applications in robotic grasping. There have been a number of studies on finger impedance in both the robotics and biological fields. They almost exclusively consider only stiffness and viscosity. However, inertia may play an important role in certain grasps, and is important for calculation of the other impedance properties. This paper reports current progress of a project to create a geometric model of the hand for predicting hand/grasp inertia at different configurations (sensed by a glove that measures joint angles) during a variety of tasks.

1 Introduction

There is an abundance of literature on grasping, covering both robotic and human studies. In a comprehensive review, Shimoga [1996] reduced the different grasp quality measures to four mutually independent properties that "an articulated force-closure grasp must possess in order for it to be able to perform everyday tasks similar to those performed by human hands". These are dexterity (configuration of grasping fingers), equilibrium (how hard to squeeze the object being grasped), stability and dynamic behaviour. Simplistically, dexterity entails the placement of fingers on the grasped object and equilibrium entails the forces exerted by the fingers. Dynamic behaviour consists of movement kinematics (velocity, and acceleration), and stability (i.e., the ability to return to equilibrium).

In order to satisfy dynamic and stability requirements, the impedance of the fingers and grasp as a whole needs to be controlled. In addition, impedance is recognised to help deal with changing conditions [Kao *et al.*, 1997] and is important for creating a grasp with the desired qualities for the object and task at hand (excuse the pun) [Friedman and Flash, 2005].

The finger impedances determine the dynamics of the fingers. They can be combined, and using a grasp map to include the contact interaction between the hand and object, a measure of 'grasp' impedance can be calculated. This provides a measure of the dynamics of the object as a result of the grasp, or the dynamics of the object-finger system. A generic dynamic equation is shown in equation 1.

$$f = M\ddot{x} + B\dot{x} + Kx \tag{1}$$

Impedance is comprised of dynamic and static components. The static component, K, is stiffness or elasticity. It represents a spring, and is a measure of the displacement that would result from a force. The dynamic component is further divided into damping, B, and inertia M. These represent the ratio between force and velocity, and force and acceleration, respectively.

Many studies have focussed on impedance in the context of manipulator control - stability and dynamic behaviour. Shimoga [1996] reported many studies that investigated impedance, all of which had a focus on the stiffness properties only. In recent years, research on robotic grasp stability and dynamic impedance has similarly neglected inertia. Li [1998] investigated the dynamic grasp stability using Liapunov analysis for different contact forces. Svinin [1999] studied rotational stability of a rigid body under constant contact forces. Lin [2000] developed a quality measure for compliant grasps and fixtures based on stiffness and later extended the stiffness models used in previous studies to encompass a variety of nonlinear contact models [Lin *et al.*, 2004].

Li et. al. [1998] have shown the importance of stiffness and viscosity due to the requirement that for dynamic stability, there must exist positive definiteness of the viscosity and stiffness matrices due to the Liapunov stability criterion. However, "dynamic forces can be significant, particularly when the manipulation velocity is relatively high or when the grasped object and finger in-

ertias collectively produce significant inertial forces during manipulation" [Shimoga, 1996]. Therefore, knowledge of the grasp inertia for a given hand configuration is likely to improve dynamic control as well as stability. In addition, control of inertia may be important for certain tasks; which can be revealed through human studies.

From another perspective, a number of studies have investigated hand impedance in human grasping. Kao [1997] investigated the stiffness of the thumb and index finger in a plane, Milner [1998] studied the effect of finger posture and voluntary forces on stiffness, Van Doren [1998] and Buttolo [1996] measured the stiffness of a grasped object and Jindrich [2004] investigated the impedance of finger joints during tapping on a computer keyboard keyswitch, modeling the finger as a spring-damper system. Hajian [1997] experimentally measured the inertia of the index finger whilst fully extended, under abduction and extension of the metacarpophalangeal (MCP) joint. However, this does not provide enough information to predict the effective endpoint mass for other configurations. Friedman [2005] calculated grasp stiffness during certain grasping tasks, and calculated the resulting stiffness ellipsoids oriented with respect to the object frame, showing that hand stiffness can be task dependent.

These studies have shown that grasp impedance is an important factor controlled by humans in order to achieve the desired task dependent grasp. Stiffness has been the focus of the research. However, dynamic impedance may also be important as an independent factor. In addition, in order to measure the stiffness and/or viscosity accurately, the inertia must also be considered.

This study investigates grasp impedance with a focus on inertia. Stiffness and viscosity are functions of link configuration and muscle activation. These parameters are typically measured by observing the finger displacement due the application of a known force. However, this is very difficult to accomplish accurately and meaningfully during the performance of a grasping task.

Unlike viscosity and stiffness, inertia is theoretically a function of link configuration alone. Therefore, if the geometry of the link and link segment inertia tensors are known, the link or finger inertia can be calculated solely from the link configuration. This provides a convenient way to calculate the inertia of a human grasp during object manipulation, and could be used to control a robotic hand.

These details can be known *a priori* for a robotic hand. However, in order to study a human hand, it is more difficult. In this work, we have developed a geometric model. This is part of an overall project that is in progress. The accuracy of the geometric model is to be tested experimentally by measuring the endpoint inertia of human fingers at several configurations and comparing this to predictions from the model.

For other body parts, there has been extensive work on studying the inertial characteristics and developing geometric models. However, relatively few works have considered the inertia of the fingers and of a grasp. Sancho-Bru et al. [2001] proposed a dynamic model of a finger, and noted the importance of inertial effects when considering fast movements.

This paper gives a brief introduction to the mathematics used for calculating grasp impedance, describes the geometric model of the hand and some preliminary results for three tasks.

2 Mathematical Background

We will be studying the dynamic equation for an object subject to a grasp made up of several fingers in contact with an object. For a thorough mathematical treatment, see [Murray *et al.*, 1994]. All grasps are assumed to be pad opposition grasps, where the finger only makes contact with the object at the fingertip.

We make use of three reference frames. The world frame, the contact frame, and the object frame. The object frame's origin is at the centre of mass of the object. Its orientation is arbitrary, but remains fixed. The contact frame's origin is at the point of contact, and it is oriented with the z-axis normal to the surface of the object.

The fingers cannot exert arbitrary forces on the object, being subject to friction constraints. A soft finger contact model is used, where three force components and the moment about the z-axis of the contact frame are transmitted. This is expressed by the matrix B_c which transforms forces at the finger endpoint, to forces experienced by the object.

2.1 Grasping Impedance

We use a linear second-order lumped element model common in impedance studies. The calculated impedances are instantaneous, and therefore considered to be constant allowing linearisation of the dynamic equation.

The dynamic equation (expressed in workspace coordinates) for the grasped object as a result of the grasp is given:

$$F_{ob} = M_{ob}\ddot{X} + B_{ob}\dot{X} + K_{ob}X \tag{2}$$

where each impedance term is a 6x6 matrix relating a force wrench F_{ob} to object motion represented by the twist X. A twist is a way of representing translational and rotational motion as a translation and rotation along an axis. See [Murray *et al.*, 1994] for more detail.

The impedance terms are calculated by combining the endpoint impedances of each finger (transformed into the object frame) while compensating for the contact interaction between finger and object.

Using the inertia term as an example:

$$M_{ob} = \sum_f G_f B_c^T Mep_f B_c G_f^T \quad (3)$$

where Mep_f, the endpoint inertia impedance term, gives the torque and forces at the endpoint of finger f as a result of angular acceleration, for each finger. B_c is the contact model, and transforms the forces at the endpoint to the forces that can be exerted on the object. It is identical for every finger. G_f is the grasp map for finger f and transforms forces from the contact frame to the object frame. The summation is carried out for each finger that participates in the grasp, giving the object inertia term.

2.2 Inertia

The endpoint inertia term for each finger, which is required in order to calculate the impedance as shown above, can be calculated from knowledge of the geometry of the finger or manipulator. This also applies to the mobility, which is equal to the inverse of the inertia. They are given by:

$$Mep = J^{-T} Mch J^{-1} \quad (4)$$

$$MOBep = \frac{1}{Mep} = JMch^{-1}J^T \quad (5)$$

where J is the conventional manipulator Jacobian, mapping endpoint velocity (local parameterisation) to joint angles.

Mch is the chain inertia, and maps angular acceleration of the joints to torques at the joints. It is given by:

$$Mch = \sum_i (J_i^b)^T \mathcal{M}_i J_i^b \quad (6)$$

where J_i^b is the body manipulator Jacobian for link i, which relates the body velocity to joint angles (the body velocity is the velocity of a rigid body in the instantaneous body frame). The summation is carried out over all the links in the manipulator (in this case a finger). Each link has a body Jacobian. $\mathcal{M}$ is the generalised inertia tensor for link i. Given by:

$$\mathcal{M}_i = \begin{pmatrix} m\mathrm{I} & 0 \\ 0 & \mathcal{I} \end{pmatrix} \quad (7)$$

where m is the mass, and $\mathcal{I}$ is the inertia tensor of link i.

3 Hand Geometric Model

Each finger is represented as a multi link chain, where each link is a homogeneous cylinder. This is a simplification, as human fingers consist of a non cylindrical bone, surrounded by non homogeneous flesh. However, the broad features of finger inertia are likely to be the same, and this is an investigation into the feasibility of such a geometric model. The hand model used is shown in Figure 1. The task is to study the 'grasp' impedance rather than the hand as a whole. As a result, only the fingers are considered, with respect to the palm. This is considered to be the important factor that is most varied for pad opposition contact grasps. For the index to pinkie fingers, this involves the segments from the knuckle up, or from the ABD/MPJ joints. For the thumb, all the segments above the TR joint are considered.

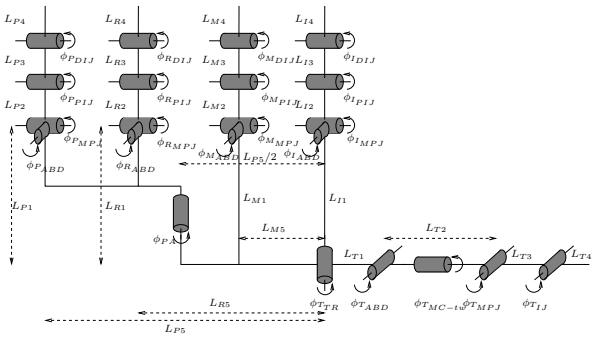


Figure 1: Hand Model.

As reported in [Zatsiorsky, 2002], the hand (including palm) orientation significantly alters the effective endpoint mass of the arm for certain tasks such as hitting a ball with a racquet. This work could be later extended to cover these scenarios as well.

3.1 Implementation of model - Predicting Grasp Inertia

Apparatus

Throughout the experiments, the CyberGlove (Immersion), and Fastrak (Polhemus) were worn by the subject, in order to record joint angles and hand position. The experimental setup is identical to that described in [Friedman and Flash, 2005].

CyberGlove The CyberGlove is a tight fitting glove with multiple strain gage sensors located over or near the joints of the hand and wrist. It was used to measure 22 joint angles of the hand. The relationship between the raw sensor output and joint angles is predominantly linear, but there is a subject-dependent component, and a calibration procedure was performed to find the parameters. The joint angles were sampled at 90Hz throughout the recordings. The 3D locations of the joints (including the fingertips) were estimated using a model of the hand based on the model presented in [Turner, 2001] and shown in Figure 1.

Fastrak The Fastrak sensor is a small box worn at the back of the wrist. It records 3D position and orientation by sensing an AC electro-magnetic field. Data were recorded at 120Hz and then re-sampled to 90Hz so as to coincide with those from the CyberGlove.

Experimental procedure

Matlab (MathWorks) was used to implement the model using the equations and hand model described above. A healthy male subject aged 27 wore the CyberGlove and Fastrak and was required to perform three tasks: Lifting a cup from the side, from the top, and unscrewing a lid (see Figure 2). The endpoint inertia for each finger and the grasp inertia was calculated for each scenario at the onset of the task.

(a) Cup lift from side.

(b) Cup lift from top.

(c) Unscrew jar.

Figure 2: Grasping tasks.

Processing data for input to the geometric model

The Fastrak and CyberGlove data were combined to give the joint locations relative to the laboratory fixed reference frame. The joint locations were then transformed into a reference frame with its centre located at the centre of mass of the object. The object's position was then determined from the locations of the fingertips grasping the object relative to their location at the start of the movement, based on the assumption that the fingertips did not change position relative to the object. The position and orientation of the object were then described using Procrustes analysis (implemented using the Statistics toolkit in Matlab), which finds the best linear transformation of the fingers from the initial to the current position.

In order to calculate the endpoint inertia (equation 4), the model requires the geometry of the hand (lengths and diameter of segments), and joint angles for a given pose. These were obtained as described above. The geometry of each link was used to calculate the generalised inertia matrix (equation 7). For a given hand orientation, the Jacobians could be calculated (they are a function of joint angles and segment lengths), allowing a calculation of the endpoint mobility for each finger using the equations shown above in Section 2.

In order to calculate the grasp inertia (equation 3), the model must calculate the Grasp Map which requires a transformation to the object frame. The position of the object was calculated as described above.

Both the endpoint and whole grasp inertia/mobility is represented as a 6x6 matrix. The upper left quadrant relates translation force to translational acceleration, and the lower right quadrant relates rotational force to rotational acceleration.

Each of these can be used to plot an ellipsoid, which provides a convenient visual representation showing magnitude and orientation of the different aspects of the inertia/mobility. The ellipsoid represents the locus of

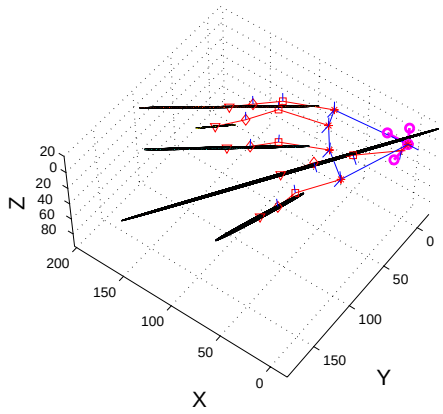


Figure 3: Lifting a cup from the top - translational endpoint inertia ellipsoids. The axis units are (mm) for the hand, and (N.s^2/mm) for the inertia ellipsoids. The thumb inertia was scaled by a factor of 0.1, and the other fingers by a factor of 0.5.

the force vector that would result from a unit acceleration rotated in all possible directions. The principal axes of the ellipsoid are given by the eigenvectors of the inertia/mobility matrix, and their magnitudes are given by the eigenvalues. This technique has been used by many researchers for biomechanics studies to visualise stiffness as well as other properties [Mussa-Ivaldi *et al.*, 1985], [Flash and Mussa-Ivaldi, 1990], [Tsuji *et al.*, 1995], [Tee *et al.*, 2004].

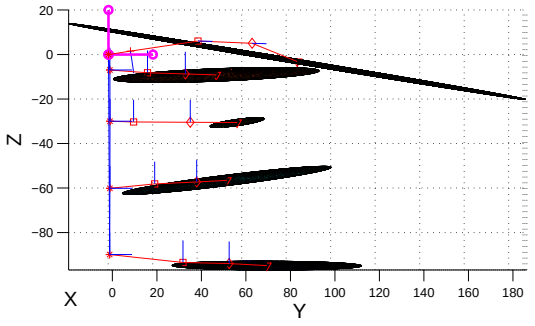
3.2 Results and discussion

The endpoint inertia ellipsoids are shown superimposed on a wireframe of the hand, at four viewpoints for the second task, lifting the cup from the top. Following this, the grasp/object inertia ellipsoids are shown for the three tasks, for both translational and rotational inertia.

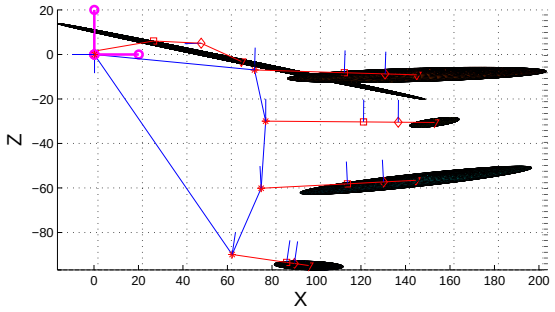
On visual inspection, the orientation and magnitude of endpoint ellipsoids is as expected, with the principal inertia component for each finger approximately parallel to the final segment, and oriented in the plane formed by the finger segments, as was found for the whole arm [Tsuji *et al.*, 1995]. However, practical experiments are required to verify the validity of the model. We are currently conducting such experiments.

The thumb inertia was significantly larger than that of the other four fingers. This may be a result of the different geometry, and contribute to its ability to oppose the other fingers and balance the grasp, beyond simply being oriented opposite them.

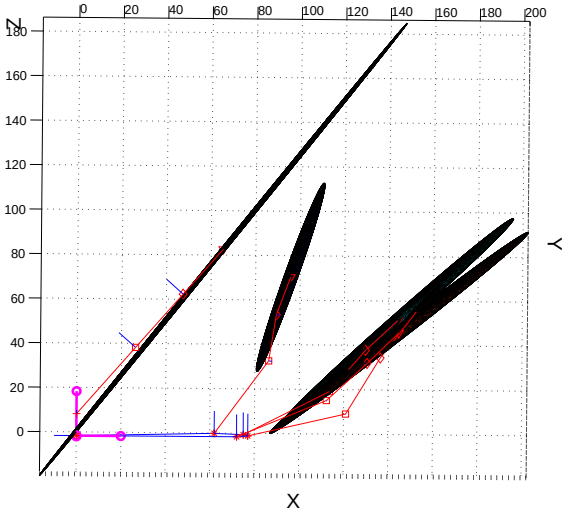
The predicted magnitude of the endpoint inertia is a significant component of the impedance, when compared to stiffness values calculated in the experimental work reported in the literature. This becomes important



(a) From x



(b) From y



(c) From z

Figure 4: Lifting a cup from the top - translational endpoint inertia ellipsoids - orthogonal viewpoints. The axis units are (mm) for the hand, and (N.s^2/mm) for the inertia ellipsoids. The thumb inertia was scaled by a factor of 0.1, and the other fingers by a factor of 0.5.

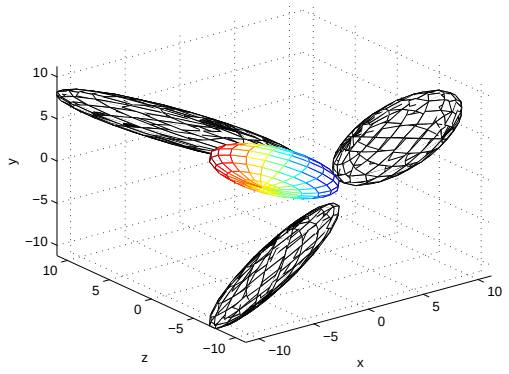
with significant acceleration (not for static conditions). Friedman [2005] found that "fingertip stiffness matrices have diagonal elements ranging from approximately 50 N/m to 1000 N/m", which were of similar range to the values reported in [Kao *et al.*, 1997] and [Milner and Franklin, 1998]. The principal component of fingertip endpoint inertia predicted by the geometric model was typically in the range of 20 to 120 N.s^2/mm for index to pinkie fingers, and approximately 1000 N.s^2/mm for the thumb.

For the index to pinkie fingers, the predicted magnitude of inertia may be two orders of magnitude less than the experimentally measured stiffness (depending on orientation and direction of displacement). Therefore, for a 10mm displacement of the finger (in the direction of maximum stiffness), an acceleration of 1000 mm/s^2 would be required to produce an equivalent opposing force, or 'effective mass'. This is only $1/10^{th}$ the acceleration due to gravity. The significance of the predicted inertia confirms that it is important to consider it when experimentally measuring the finger/grasp impedance terms stiffness and viscosity.

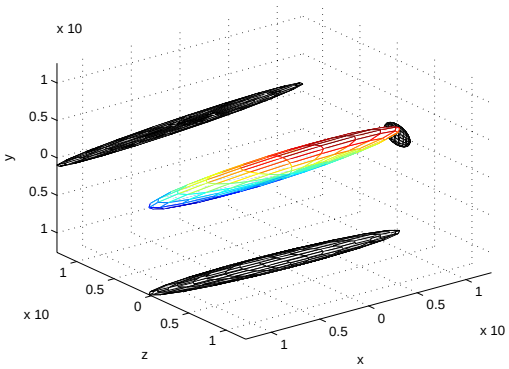
The results suggest that the grasp inertia is task dependent, as shown for stiffness [Friedman and Flash, 2005]. For the task of lifting the cup from the side, it is most inert for horizontal motion along the direction collinear with the fingers. The grasp is most inert for rotation about an axis parallel to table surface. For the task of lifting the cup from the top, the grasp is most inert for rotation about the axis perpendicular to the table surface, and for vertical translation. For the case of unscrewing the jar lid, there was a similar hand configuration as to lifting the cup from the top. This is reflected in the similar inertial characteristics. However, the translational inertia is wider, which is likely to be a result of spreading the fingers around the lid.

The inertial characteristics of the grasp appear to be a secondary result of the hand configuration necessary to perform the required task, rather than a characteristic that aids the task. However, the strong task dependence demonstrated is interesting, and requires further investigation.

The magnitude of grasp/object inertia is significant when compared to stiffness experiments. The maximum grasp inertia is typically in the order of 10 Ns^2/mm compared to values in the range of 200 to 800 N/m [Friedman and Flash, 2005]. Therefore, the grasp inertia may have a significant impact on the grasp impedance magnitude and orientation.



(a) Translational (N.s^2/mm)

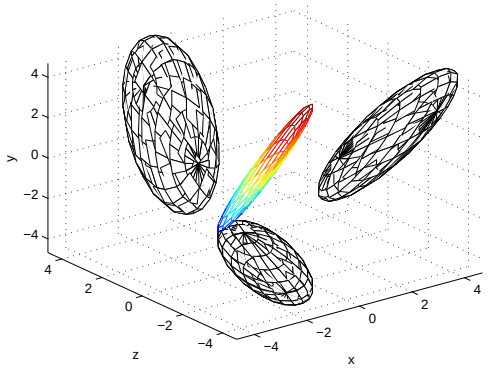


(b) Rotational (mN.mm.s^2)

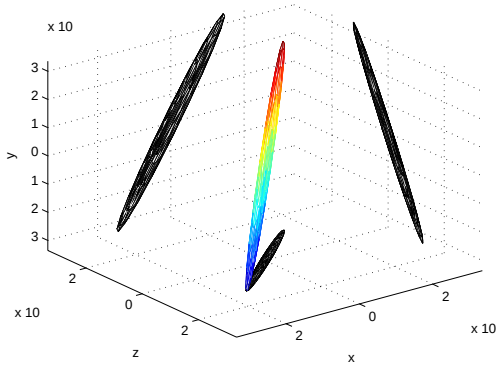
Figure 5: Lifting a cup from the side - grasp inertia.

4 Conclusions

Inertia has not been considered in past studies of hand impedance. However, it may be important for grasping, and for calculating the other impedance terms in

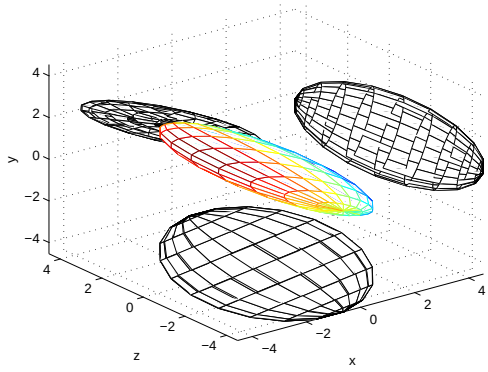


(a) Translational (N.s^2/mm)

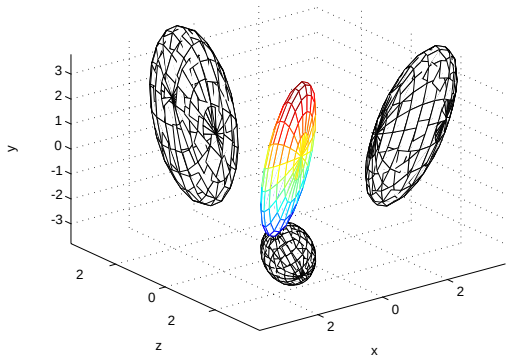


(b) Rotational (mN.mm.s^2)

Figure 6: Lifting a cup from the top - grasp inertia.



(a) Translational (N.s^2/mm)



(b) Rotational (mN.mm.s^2)

Figure 7: Unscrewing a jar - grasp inertia.

studies on human grasping. This work in progress is a first step. A geometric model has been developed. It is able to provide valuable information for studying human grasping. Preliminary results analysing the inertia of the hand/object grasp for several tasks have been carried out. They show that the inertia is a significant component of impedance, and should therefore be considered in impedance studies, for more accurate stiffness and viscosity measurements/calculations. In addition, this study has shown that the inertia is characteristic of the task.

This is a preliminary experiment to demonstrate the usefulness of the geometric model. Further more in depth inertia prediction experiments will be carried out to determine if the grasp inertia characteristics are controlled. In addition the model is currently being tested with finger inertia experiments.

Acknowledgements

I wish to thank Professor Tamar Flash for hosting me at the Vision and Robotics Laboratory at the Weizmann Institute of Science for a period of exchange.

The research was made possible through funding provided by a fellowship from the Australia Israel Scientific Exchange Foundation and a grant from the Centre for Perceptive and Intelligent Machines in Complex Environments.

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