The Grasp Perturbator:
Calibrating human grasp stiffness during a graded force task

Hannes Höppner, Dominic Lakatos, Holger Urbanek, Claudio Castellini and Patrick van der Smagt

Abstract— In this paper we present a novel and simple hand-held device for measuring *in vivo* human grasp impedance. The measurement method is based on a static identification method and intrinsic impedance is identified inbetween 25 ms. Using this device it is possbile to develop continuous grasp impedance measurement methods as it is an active research topic in physiology as well as in robotics, especially since nowadays (bio-inspired) robotics can be impedance-controlled. Potential applications of human impedance estimation range from impedance-controlled telesurgery to limb prosthetics and rehabilitation robotics. We validate the device through a physiological experiment in which the device is used to show a linear relationship between finger stiffness and grip force.

I. INTRODUCTION

One of the most prominent features of modern robotic systems is their ability to be controlled in impedance mode. Mimicked from biology, the goal is not to reach a desired Cartesian position with the utmost accuracy, but rather to maintain a certain impedance (cf. stiffness) in order to be prepared solving tasks while being in contact with the environment.

Our institute has a long history of implementing impedance control algorithms for robotic arms and hands, and has successfully demonstrated its applicability in various tasks. As our robotic systems grow in complexity, however, while increasing their dexterity—from a kinematic, dynamic and impedance point of view—additional, the question arises of how to cope with this parametrical freedom. Many rules-of-thumb exist to handle impedance: when accurate, use high impedance; when moving fast, use low impedance; a detailed analysis of this parameterisation is desired. Therefore we investigate human impedance behaviour with the goal of transferring general approaches to robotic systems.

In this paper we investigate human finger impedance, in order to quantify finger stiffness with respect to exerted force. In our assumption, finger stiffness is directly correlated to exerted finger force and can be reconstructed from that signal. In order to support this assumption, we developed a small, hand-held device which can exert finger position perturbations while measuring the exerted force—thus determine the stiffness of the grasp holding the object. This device, which we call the "Grasp Perturbator, is small enough to be held between index finger and thumb (Figure 1).

Using this device, we demonstrate the near-linear relationship between finger stiffness and exerted finger force,

The authors are with the Institute of Robotics and Mechatronics, German Aerospace Center (DLR), D-82234 Oberpfaffenhofen, Germany {hannes.hoeppner, dominic.lakatos, holger.urbanek, claudio.castellini, smagt}@dlr.de
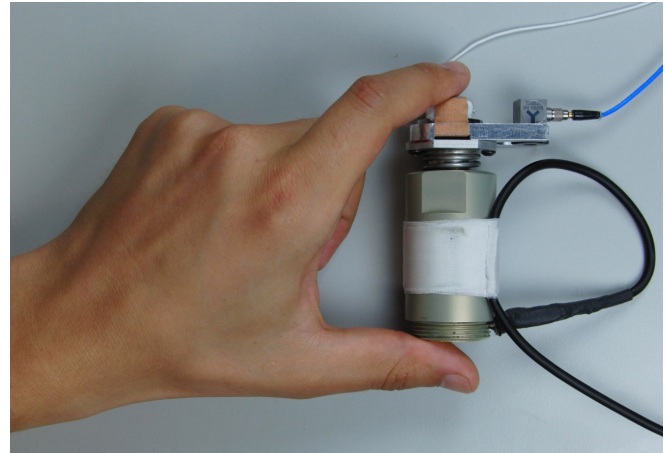
Fig. 1. The Grasp Perturbator held by a human subject in a pinch grip.

thus allowing simple grasp force measurement to replace impedance measurement in future investigations. With this result, we can easily determine grasp impedance in various settings in order to quantify human grasp impedance rules.

A. Related work

Previous research on measuring human impedance has focussed primarily on the arm [1], [4], [12], [14], [16]. Most of these papers refer to Hogan's pioneering work [9]. Different measurement apparatuses have been developed, mostly planar position perturbation devices; the experience with these apparatuses and the methods used in these works can also be used for identifying human finger impedance.

A method and apparatus for measuring the stiffness of the single human index finger is described in [11]. As the authors measure both finger flexion and extension and in different planar orientations of the index finger, they are able to separate conservative and non-conservative stiffness terms and can also evaluate Cartesian endpoint-stiffness (stiffness ellipses).

In order to identify the human finger stiffness the authors apply a method suggested in [12] for measuring two-dimensional static stiffness of the human arm: they measure the statically applied force before and after the perturbation, when the velocity is zero, and compute the index finger stiffness using the force difference. They find that, as is the case for the human arm, the mechanical behaviour of the index finger is mainly spring-like, and that the conservative component of the force field can be modelled with a 2D linear spring. The influence of non-conservative effects is less

than 15% of the total force response to static displacements.

In [7] Haijan and Howe suggest a method and device for the identification of mechanical impedance of the human index finger metacarpal joint in extension and abduction. One-dimensional perturbation forces between 2 and $20\,\text{N}$ for extension and between 2 and $8\,\text{N}$ for abduction are applied, with a maximal duration between 20 and $30\,\text{ms}$ in order to avoid reflexes. A pneumatic perturbation system is shown which can apply forces with a displacement of the index finger of about $5\,\text{mm}$. Using a linear, second-order translational model of the finger the authors identify inertia, damping, and stiffness with a least-squares fit. They find that all measured subjects increase their stiffness and damping of the index finger when increasing the applied bias force. In further studies, Hajian extends his research on pinch grasp impedance, validating the result that increasing force bias increases damping and stiffness [6]. He finds that the correlation between applied force bias and both damping and stiffness is almost linear.

In [8], Hasser and Cutkosky build a measurement device for measuring human grasp impedance when grasping a haptic knob, applying a rotational perturbation, rather than translational, to the pinch grip. Again, a linear, second-order translational model is used and impedance is identified with a least-squares fit. Furthermore an approximately linear increase of damping and stiffness with an increase of the grip strength to the haptic knob is found therein. Lastly, they report about the strong influence of the fingerpad impedance, and show that their model only fits for light and moderate grip forces—for stronger grip forces a higher-order model is required, taking both finger and fingerpad impedance into account.

In [10], Kao *et al.* suggest a method for identifying a grasp stiffness matrix using, again, a least-squares fit on data obtained during a pinch grip task. The apparatus used consists of two disks connected to a torque motor with two cantilevers. Strain gauges are printed on both cantilevers in order to measure the grasp forces of both, index finger and thumb separately. The setup can also measure applied tangential forces: the subjects are instructed to grip the disk tightly while their arm and the wrist are blocked, and to move the disk in the proximal/distal and radial/ulnar directions. The first objective of this study was to find out more about calibration methods for robotic hands; the authors find that a symmetrical calibration method that excludes non-conservative components of the stiffness matrices suffices. Similar to [11], they claim that the non-conservative components of the stiffness matrices are negligible during human grasping, and that relaxing the arm blockage induces a smaller stiffness and a higher compliance.

II. THEORETICAL BACKGROUND

A. Stiffness

Stiffness of the pinch grip, that is the quantity we are interested in measuring here, is the relation between force and displacement of the index finger with respect to the thumb. Considering one degree-of-freedom (DoF), that is the change in the distance between the thumb and index fingertips as a linear motion along a cartesian axis, a displacement from an equilibrium posture causes a force in the opposite direction to try and restore the previous state. This model of stiffness is a one-DoF simplification of the multi-joint case described in [9] and is expressed by the following scalar equation:

$$F = -K \cdot \Delta x, \quad \text{where} \quad K = K(x,t) = -\frac{\partial F}{\partial x}. \quad (1)$$

F : Force
Δx : Displacement
K : Stiffness

In general, the relation between force and displacement is neither linear nor continuous, but for small displacements during a postural task, Taylor's approximation of (1) holds:

$$\hat{K} = K^\star + \left.\frac{\partial K}{\partial x}\right|_{x_0} \Delta x + \left.\frac{\partial K}{\partial t}\right|_{t_0} \Delta t. \quad (2)$$

During an equilibrium posture we assume that the time dependency of stiffness is due to the muscle activation, controlled by the central nervous system (CNS). Since the transmission time between the CNS and the muscles driving the finger is at least $25\,\text{ms}$ [15], the last term of (2) is zero; substituting the second term of the right hand side in (2) with the definition of the stiffness in (1), that is $\partial K / \partial x = -\partial^2 F / \partial x^2$, one obtains a second order term for the force, which is negligible and leads to a constant approximation of stiffness:

$$\hat{K} = K^\star(x_0, t_0) = \text{const.} \quad (3)$$

The parameter $K^\star$ in (3) is a local linearised model of stiffness about the working point x_0, when $t - t_0 \leq 25\,\text{ms}$. This model will be used from now on.

B. Evaluating Stiffness

To identify pinch grip stiffness of a mechanical one-DoF system the standard linear time-invariant equation of motion is used:

$$m\ddot{x}(t) + r\dot{x}(t) + kx(t) = f(t). \quad (4)$$

$x, \dot{x}, \ddot{x}$: position and its time derivations
f : external force
m : constant mass parameter
r : constant velocity proportional damping
k : stiffness (as defined in Eq. (3))

Usually in the general case the system is perturbed by an external force $f(t)$ and the motion response over time is measured, leading to an estimate of the instantaneous stiffness. Repeating this experiment and using a least-squares fit as in [4] for arm stiffness yields an overall estimation of stiffness. The frequency bandwidth of the perturbation must contain the natural frequencies of the considered system, in order to get a response which quantitatively represents the system [13]. If the perturbation does not fulfill this condition one can obtain physically meaningless impedance parameters [17].

Since here we are interested in grasping as a postural task at equilibrium, the static stiffness estimation method first

described by [12] can be used. In particular, we consider the average force response during two time intervals T_1 and T_2, before and after the perturbation, where $\dot{x} = \ddot{x} = 0$, so that Eq. (4) reduces to $kx(t) = f(t)$ and stiffness can be estimated by

$$k = \frac{E_{T_2}(f) - E_{T_1}(f)}{E_{T_2}(x) - E_{T_1}(x)}, \qquad (5)$$

where $E_T(\cdot)$ denotes the average over time interval T. Figure 2 shows a typical example measurement.
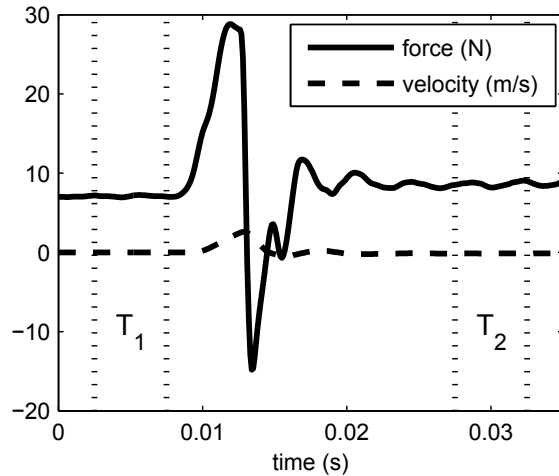

Fig. 2. Typical stiffness estimation. Vertical dotted lines denote T_1 and T_2. The total timespan of the perturbation is always less than $25ms$.

III. DEVICE DESCRIPTION

The proposed device[1] works by position perturbation, i.e., it displaces the relative position of thumb and index by a known distance and measures the reaction force exerted by the fingers. During the operation it is held between thumb and index finger in a pinch grip, as defined in standard grasping taxonomies, see, e.g., [2]. Figure 1 shows the typical operation.

Figure 3 shows the device in detail. A rigid and a moving part are coupled by a linear spring; an electromagnet is mounted on one extremity of the moving part, with the aim of pre-loading the spring. As the electromagnet is turned off, the spring is released and pushes the two sections apart, until the mechanical stop mounted onto the rigid part is reached by the moving part. The distance between the electromagnet and the mechanical stop, that is the imposed position displacement, is known; two on-board sensors measure the applied force as well as the acceleration. The stiffness, the initial tension of the spring, and the displacement between the rigid and co-moving part can easily be adjusted before the beginning of the measurement.

Notice that at this stage the electromagnet cannot automatically reload the perturbator, which must therefore be preloaded by hand after every measurement (no bidirectional

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[1]Patent pending

Fig. 3. The Grasp Perturbator; from left to right: electromagnet, moving part, rigid part, whole.

or oscillating perturbation is possible). Furthermore, stiffness during flexion tasks only can be measured.

The dimensions of the device are $35\,\mathrm{mm}$ in diameter and $85\,\mathrm{mm}$ in height when the spring is not preloaded and its weight approximates $217\,\mathrm{g}$. The displacement of the position perturbation is approximately $10\,\mathrm{mm}$. The force of the spring of the preloaded device used in the experiments is about $100\,\mathrm{N}$ when loaded and $70\,\mathrm{N}$ when unloaded; this ensures that the force exerted by the device is always larger than the applied finger force, so that position perturbation is always constrained.

The measurement setup consists of a host running Windows, and a real-time target machine running QNX where a Matlab/Simulink model to control the device is running at $10\,\mathrm{kHz}$ sample frequency. The sensors signals are amplified and measured with an analog digital converter and the electromagnetic field is switched using a relay card; the cards are directly connected to the real-time machine. The acceleration signals are additionally filtered with an analog $3\,\mathrm{kHz}$ low-pass filter. The acceleration sensor can measure translational accelerations in all three dimensions with a sensitivity of $1.02\,\mathrm{mV}/\frac{\mathrm{m}}{\mathrm{s}^2}$ and a measurement range of $\pm 4905\,\frac{\mathrm{m}}{\mathrm{s}^2}$ pk. Its bandwith along the z-axis is $2\,\mathrm{Hz}$ to $10\,\mathrm{kHz}$. The nominal sensitivity of the force sensor is $1\,\mathrm{mV/V}$, the nominal range $1\,\mathrm{kN}$.

IV. EXPERIMENTAL SETUP AND RESULTS

A. Materials and Methods

Five healthy male subjects, four right- and one left- handed (subject C), age 26–39 yrs., joined an experiment designed to measure their finger stiffness while pinch-gripping the proposed device. They had no knowledge about the experiment itself.

The Grasp Perturbator was put without any fixation on a table. The subject was asked to sit comfortably in front of the table, relax and let the dominant arm lie on the table in order to be able to grasp the device with the thumb and index finger. Middle, ring and little finger would lie bent and relaxed below the palm (see Figure 1). It was stressed that the subject should relax as much as possible also while grasping, in order to minimize disturbances to the finger stiffness induced by the hand/arm/body muscle tension.

Initially, the subject was instructed to pinch grip the device as firmly as possible for 10 seconds, while his maximum gripping force was estimated (resulting in values between 25 and 40 N). Subsequently, he would be shown a live visualisation of the force applied to the device, and two lines representing 1.15 and 0.85 times a required amount of force; he would then be instructed to reach that level with the aid of the bands, and keep it until the perturbation was felt. The perturbation was issued at a time chosen randomly between 2 and 4 seconds after the reaching of the required force. The amount of force (Normalised Force Level, NFL) was either $10, 20, 30, 40, 50$ or 60% of the maximum gripping force measured beforehand.

This stimulus/response cycle was repeated 10 times per level (total 60 times per subject) in a randomised order. In-between cycles, the experimenter would pre-load the spring, reset the force sensor and check once again the muscular relaxation of the subject. If the subject reported fatigue, he would be allowed to rest as much as needed. The experiment lasted on average 18 minutes and no subject reported uneasiness.

B. Experimental Results

The mean and standard error of the mean (SEM) stiffness values are listed in Table I, for each NFL and subject; each point and error bar is evaluated over the related 10 stimulus/response cycles.

Figure 4 depicts these data graphically. Also, for each subject we show a least-squares linear fit, the related R^2 coefficient (values of R^2 close to 1 denote a perfect linear regression) and the linear regression slope, α.

As can be seen, the relationship between stiffness and the required force level is essentially linear ($R^2 \geq 0.96$) and the order of magnitude of the regression slopes is the same for all subjects.

V. DISCUSSION AND CONCLUSIONS

In this paper we have described and demonstrated a novel hand-held device, the Grasp Perturbator, which can be effectively used to measure *in vivo* human grasping stiffness. Assuming that grasping stiffness is correlated to finger force [6], we validate the device by showing that human subjects produce a linear increase in finger stiffness as they grip the device with linearly increasing force. Stiffness is measured according to existing literature; linearity is very strong and uniform across subjects, be they right- or left-handed ($R^2 \geq 0.96$). The whole measurement time for estimating the stiffness is less than 25 ms, thus no influence of voluntary interactions nor reflexes can distort the result. In our experiments, we only measure the intrinsic stiffness of the grasp due to tissue properties.

The measured linear relationship between stiffness and force

$$K = K(x,t) = -\frac{\partial F}{\partial x} = c_1 \cdot F(x) + c_2, \qquad (6)$$

leads in solving the differential equation to

$$F(x) = k_1 \cdot \exp(k_2 \cdot x) + k_3, \qquad (7)$$

where c_1, c_2 and k_1, k_2, k_3 are constants. This result implies that there is a nonlinear intrinsic exponential relationship between force and displacement. Thus these measurements confirm to a model of the pinching hand in which the muscles are represented by (nonlinear) exponential elements [3]. This representation is relevant in the design of variable-impedance robotic hands, where such linearity may influence the mechanical design of the actuators.

The Grasp Perturbator relies on an extremely simple idea: a fixed position displacement is obtained using a spring and an electromagnet, and a force sensor is then used to measure the countering force applied by a human subject. The device is small and can be hand-held. Comparing to existing measurement devices it excels with its simplicity. In future work we will develop continuous *in vivo* impedance identification techniques by using EMG and other muscle properties measuring methods and calibrating them to stiffness with the proposed device. Further, even lighter and smaller versions will be potentially employed to measure stiffness during more complex operations (e.g., during teleoperated surgery). These techniques will help us in paving the way to sophisticated forms of impedance-controlled teleoperation for example using the DLR hand-arm system [5], or for teleoperated surgery and for new types of prosthetic hands with variable stiffness.

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TABLE I

MEAN ± ONE SEM STIFFNESS VALUES (N/M) FOR EACH SUBJECT (ROWS) AND NFL (COLUMNS). EACH POINT IS EVALUATED OVER 10
STIMULUS/RESPONSE CYCLES.

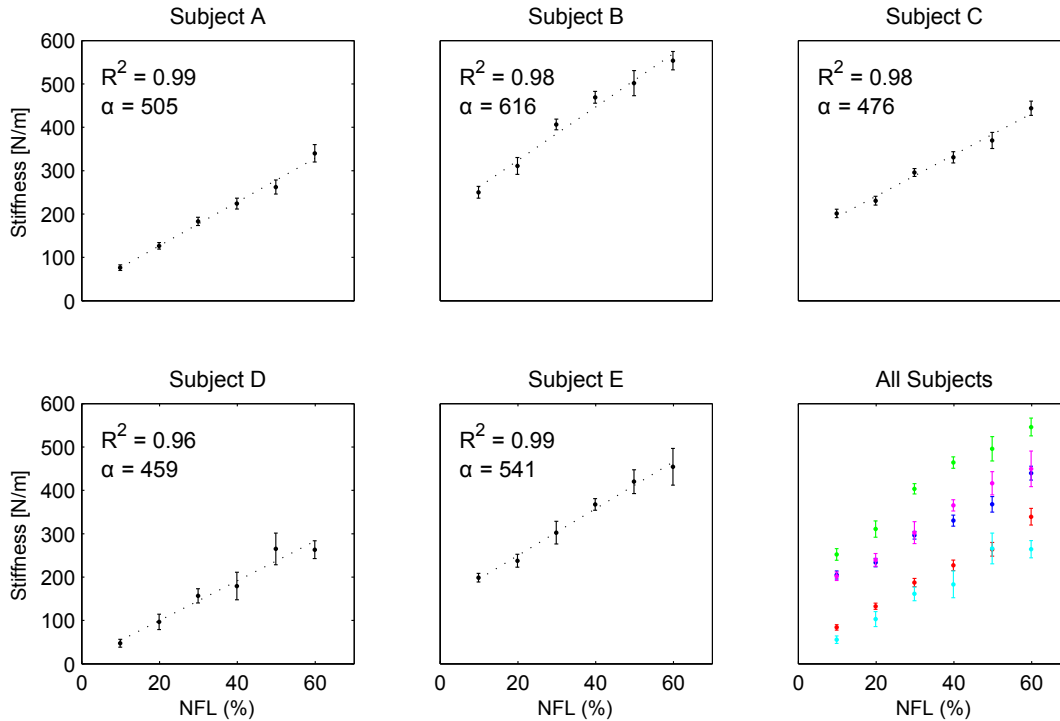|	10%	20%	30%	40%	50%	60%
A	76 ± 6	126 ± 7	183 ± 10	224 ± 13	262 ± 16	340 ± 20
B	250 ± 14	310 ± 19	406 ± 12	469 ± 14	502 ± 29	554 ± 21
C	201 ± 10	230 ± 10	295 ± 9	330 ± 13	369 ± 19	444 ± 17
D	47 ± 9	96 ± 18	156 ± 16	178 ± 32	264 ± 37	262 ± 20
E	198 ± 10	237 ± 15	302 ± 26	367 ± 13	419 ± 28	454 ± 42

Fig. 4.   Graphical representation of the estimated stiffness per each subject and Normalised Force Level NFL.

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