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# Preliminary design of a novel system for estimating end-point stiffness

Lorenzo Masia, Giulio Sandini and Pietro Morasso

*Abstract*— **Quantification of arm stiffness is of great interest for a wide group of different research branches, because modulation of muscular stiffness represents the principal mechanism of motor control of movements. Past literature concentrated efforts in defining different methods to identify multijont hand stiffness, but the required computational burden make them hard to implelement. In the present work we aim to propose a novel design of a single degree of freedom mechanism conceived to estimate arm stiffness in a reduced amount of time; a rotary mechanism coupled to a commercial six axes force sensor allows to apply known cyclic radial perturbation to the human arm and acquiring the restoring forces. The outcomes have reported that the device is reliable and stiffness measurements on a test bench can be performed in a reduced amount of time (about 1 second). A modular system has been also developed to conduct experiment on humans while performing motor adaptation.**

## I. INTRODUCTION

In the field of dynamic systems, the mechanical impedance is defined as the restoring force of the system itself in response to an imposed spatial perturbation. Neuromuscular system uses mechanical impedance modulation to preserve stability while interacting with the external environment, by means of tuning three different characteristic terms: stiffness, viscosity and inertia [1].

In multijoint arm movements endpoint impedance of the arm is the result of the interaction between agonist and antagonist muscles concurrent on a joint which are characterized by an inherently spring-like properties [2]. Most of the previous works focused the attention to the stiffness measurement, because contrarily to viscoelastic and inertial contributions, stiffness is directly modulated by the central nervous system (CNS) by changing the activation levels of agonist and antagonist muscles. The most common technique for stiffness evaluation is based on the acquisition of muscular restoring force resulting to a known displacement. The seminal work of Mussa-Ivaldi et al. [3] proposed a new experimental method using computer controlled mechanical interface to measure and represent the elastic force field associated to the posture of the arm; it consisted in observing the steady-state force responses to a series of separate one-dimensional `step' perturbations imposed from different directions; it was found that the endpoint stiffness of the human arm in the horizontal plane was primarily `spring-like' and that limb geometry had a major effect on the magnitude and directionality of endpoint stiffness. Several other studies have used similar techniques to examine the effects of external loads. Bennet et al. [4-5] and Lacquaniti et al. [6] have used stochastic force disturbance and consequently measuring the resulting change in hand position. Robot generated force impulses have been used to estimate stiffness during multijoint movements [7-11] and a further experimental investigation by Burdet et al. [12] strengthen the robustness of this technique by introducing an algorithm allowing to modulate the hand displacement relative to a prediction of the unperturbed trajectory.

A time-domain and frequency domain, multiple-input, multiple-output (MIMO) linear system identication techniques was also adopted to estimate the dynamic endpoint stiffness of a multijoint limb [13]. This last model was proposed in order to overcome the limitations showed by the previous mentioned method based on the step-perturbation. In fact estimates of steady-state stiffness, obtained using step or ramp perturbations, require that the subjects `do not intervene' in response to step or pulse changes in end-point position for intervals several times longer than stretch reflex or even voluntary reaction times. Besides the steady-state stiffness estimates, employed in most studies, ignore the much larger dynamic stiffness components that can strongly resist transient external disturbances; again the examination of the dynamic endpoint properties (inertia, viscoelasticity) was performed with a priori assumptions about the structure of the endpoint dynamics based on a second order linear model. Despite the extensive literature devoted to formulate a shared approach, impedance evaluation is still a hard issue and variability of the conditions may lead to high inaccuracy and reliability of data. Recent works were focused on the development of robotic devices characterized by high backdriveability [14-15-16]: all these systems were actually planar 2D manipulanda used to perturb human arm (shoulder and elbow) in different directions using impedance or force control schemes and consequently sensing the restoring force at the interaction between the device and the human arm. The theoretical approaches for data post processing for impedance evaluation were the ones above mentioned.

We propose a novel mechanism designed for impedance evaluation based on a modular device coupled with a commercial force sensor which can be eventually connected to the end effector of any robotic manipulandum;

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Lorenzo Masia (corresponding author), Giulio Sandini and Pietro Morasso are with the Italian Institute of Technology, Dept. of Robotics, Brain, and Cognitive Sciences, Via Morego, 30, 16163 Genoa, Italy (phone: +39 01071781458/464; fax: +39 0107170817; e-mail: lorenzo.masia@iit.it, giulio.sandini@iit.it, pietro.morasso@iit.it).

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characterized by an extremely high bandwidth and able to measure endpoint impedance in multiple directions in a reduced amount of time (about 1 second), it doesn't need for any implementation of complex control scheme to apply kinematic perturbations.

## II. MECHANICAL DESIGN

The mechanics of the system can be described by dividing the whole assembly in two main parts:

- _measuring module_: it consists of a commercial six-axes force sensor (ATI Gamma, ATI Industrial Automation, NC, USA).
- _motion generator_: the motion generator is a novel mechanism which superimposes the radial displacement to the force sensor and therefore it represents the module which applies the series of separate one-directional `step' perturbations along multiple different directions.

The motion generator is composed by a planetary gear with its sun-gear rigidly coupled to a main shaft which is connected to a minimum jerk profiled cam (figure 1A). The sun is driven by the primary actuator transmitting the motion to the whole system (brushless torque controlled electric motor).

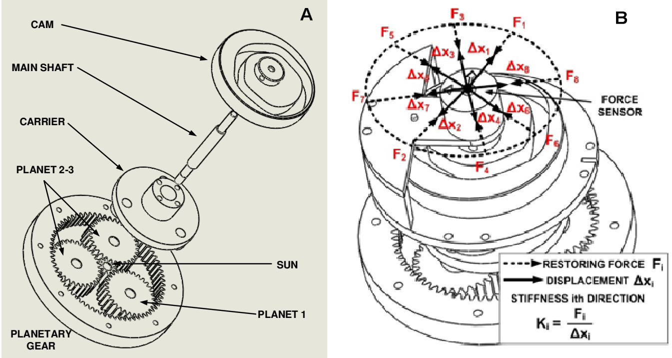

Figure 1: A:motion-generator is the assembly of a planetary gearhead and a cam mounted on the main shaft which delivers the motion. B: mechanical sketch of the assembly and radial perturbations: on the top the force sensor is rigidly connected to the end effector and superimposes different radial perturbation $\Delta X_i$ due to cam rotation over the course of planetary gear motion. Only 8 directions are depicted to simplify the sketch.

The system is designed to have a theoretical reduction ratio of 8:1; this means that 8 rounds of the *cam* and the *sun* correspond to 1 complete rotation of *carrier* which is connected to the three *planets* of the planetary gearhead. The *carrier* is equipped with linear bearings which can slide in the horizontal plane with a motion law superimposed by the cam profile. We intended to reproduce the above mentioned steady-state force responses method using directional perturbations; it requires that there be an interval during which the hand is maintained in a zero velocity position after being displaced and this interval is indicated as a plateau (figure 2). As suggested by Burdet et al. [17] in order have a good estimation of the stiffness using steady state displacement a good position perturbation must be brief, and the constant position plateau (dwell in which the force is measured) must be reached as quickly as possible.

However, a too fast or abrupt transition to the plateau requires the mechanical interface to produce high forces within a brief time, which can lead to vibration and deterioration of the force signal. A short transition phase, which minimized vibration, was achieved by designing the *cam* profile using a sixth-order polynomial with zero velocity and zero acceleration at the boundaries and zero end jerk according the following formula [18]:

$$x(\vartheta) = C_0 + C_1 x + ......... + C_5 x^5 + C_6 x^6$$

Where $x(\vartheta)$ is the imposed displacement of the *cam* as function of the *cam* rotation and $C_{0..6}$ are the unknown coefficients of the 6th order polynomial to be determined to match the design specification of jerk minimization. It was chosen a double dwell *cam* which, in 360 degrees rotation, displaces the subject's hand in two different opposite directions to input an "unpredictable" spatial perturbation (figure 2).

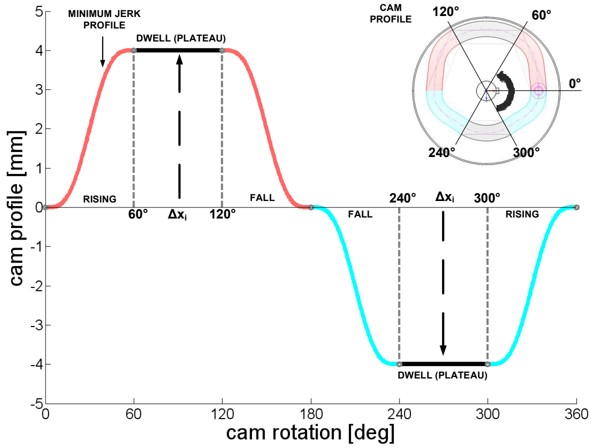

Figure 2: cam profile obtained by a sixth order polynomial allows a 4mm displacement by a double dwell minimizing the acceleration and jerk while risings. Typical 4mm perturbation superimposed to end point in order to measure the restoring force during the plateau at which the inertial contribution of the arm is negligible.

The *motion module* is used to perturb the end point in different radial directions; as previously mentioned the *carrier* is equipped with linear bearings on which the force sensor is mounted (figure 1.B) and therefore for every half rotation (180°) of the *carrier* the *cam* radially moves the force sensor in *eight* (the cam is *double dwell* for *eight* rounds the *cam profile* perturbs 8x2 times) different directions (the theoretical reduction ratio is 8:1).

Once the system starts (figure 1.B) the *cam* pushes the *sliding carriage* and the *force sensor* in one direction (direction N° 1), displacing the *subject's hand* of a certain amount $\Delta X_1$ that is defined by the geometry of the *cam profile* (4 mm is the displacement imposed by the *cam*). The *hand* force reaction $F_1$ is acquired by the *force sensor*, hence a directional value of the stiffness $K_1$ is obtained as the ratio:

$$K_1 = \frac{F_1}{\Delta X_1}$$

While the *cam* rotates, the *carrier* and the *sliding carriage* rotate with a slower angular speed, which is imposed by the *reduction ratio* of the *planetary gear* head (8:1). The next half round of the *cam* perturbs the *hand* in an opposed direction N°2 shifted with respect to the previous one of the amount of rotation made by the *carrier* and 180° because the *cam* is double-dwell. The hand is now displaced of a $\Delta X_2$ and the correspondent reaction force $F_2$ is acquired by means of the *force sensor*. The stiffness associated to the new direction will be:

$$K_2 = \frac{F_2}{\Delta X_2}$$

Since directional arm stiffness is not isotropic but strongly depends on muscular activation and posture the two evaluated stiffness $K_1$and $K_2$ are reasonably different.

When the *planetary gearhead* or the *carrier* completes half a round (180°), the system will have scanned *eight* different directions, because 8:1 is the reduction ratio of the *planetary gear* and the *cam* is double dwell, therefore eight values of directional stiffness will have been evaluated.

$$K_1 = \frac{F_1}{\Delta X_1};\ K_2 = \frac{F_2}{\Delta X_2}; K_3 = \frac{F_3}{\Delta X_3} \dots K_k = \frac{F_k}{\Delta X_k}; \dots K_8 = \frac{F_8}{\Delta X_8}$$

By means of this simple mechanism it is possible to estimates multidirectional stiffness in a very short time, with no need to perform numerous distinct trials for different directional measurements as suggested by the steady-state force responses method.

## III. METHODS AND EXPERIMENTS

### A. *Characterization of the system:preliminary test.*

Stiffness measurement is often affected by inaccuracy and systematic errors; previous methods suffer from the limitation that a perturbation of the same amplitude, during different trajectories, applied at different points in the trajectory or in different directions, will displace the hand by different amounts. This is because limb stiffness depends on joint angles, angular velocity and perturbation direction; hence the proposed mechanical device has the main goal to allow measuring stiffness without disrupting motion concentrating the acquisition in only one single trial. To characterize the system a custom setup has been developed (figure 3). It consists of a bench where the device is connected to a frame able simulate different stiffness configurations by means of calibrated springs. A preferential stiffness configuration (table I) at distinct speeds of the mechanism has been measured to test the accuracy and reliability of the device. Table I indicates the speed values at which the system performs the stiffness measurement for the chosen configuration of the springs disposed on the bench and connected to the force sensor.

Table I: experimental condition of the preliminary test

| **Rpm** | **100** | **300** | **500** | **800** | **1000** | **1200** | **1500** | **2000** |
|---|---|---|---|---|---|---|---|---|
| **Execution time [s]** | 13.47 | 4.49 | 2.69 | 1.83 | 1.45 | 1.24 | 0.96 | 0.75 |
| **Principal direction** | 90° on the plane XY of the force sensor | | | | | | | |

Figure 4 depicts to the absolute value of the force as function of angular rotation of the *carrier* and the *planetary gear* during the trials at different angular speeds of the *cam.*

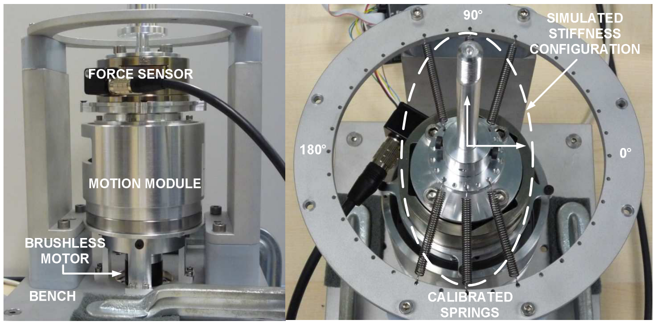

Figure 3: overview of the device (motion moduel and force sensors) connected to the bench used to simulate principal direction of stiffness by calibrated springs.

A second order Butterworth filter (10 Hz cut-off frequency) was used to clean the force signal from oscillations and noise during the acquisition. As shown in the plots, for high angular speeds (800-1200-1500-2000 RPM) despite filtering the force signal is affected by mechanical noise especially in correspondence to the *dwells* of the *cam*, where a second order oscillation arises because of an increasing contribution of inertial counterpart of the mechanics. The intervals of interest for measuring the stiffness over the different directions are the dwells of the *cam* where the springs are stretched by 4mm displacements. In this phase the amount of restoring force is acquired and divided by the actual displacement (4mm) imposed by the rotation of the *cam profile* in order to obtain every single directional stiffness which is then associated to the planetary gearhead rotation interval in which displacement is given.

Observing figure 4 it is possible to identify the force peaks for the different speed rotations corresponding to the 4mm dwells of the *cam* (2 dwells each rotation) which are not eight as expected but seven because the *cam* acts 7 time on its follower which rotates half a round with the *carrier*. Figure 5 depicts the stiffness visualizations corresponding to the measurement performed at different speeds. The dotted black ellipse is a fitting performed by nonlinear least squares, optimizing the squared sum of orthogonal distances from the points to the fitted ellipse. Observing figure 5 it is evident that the centre of the ellipse is shifted rightward; this is not due to inaccuracy or drift in the measurement but to the tolerances in mounting procedure because the centre of the force sensor and the one of the frame on which the device is mounted may not be coincident.

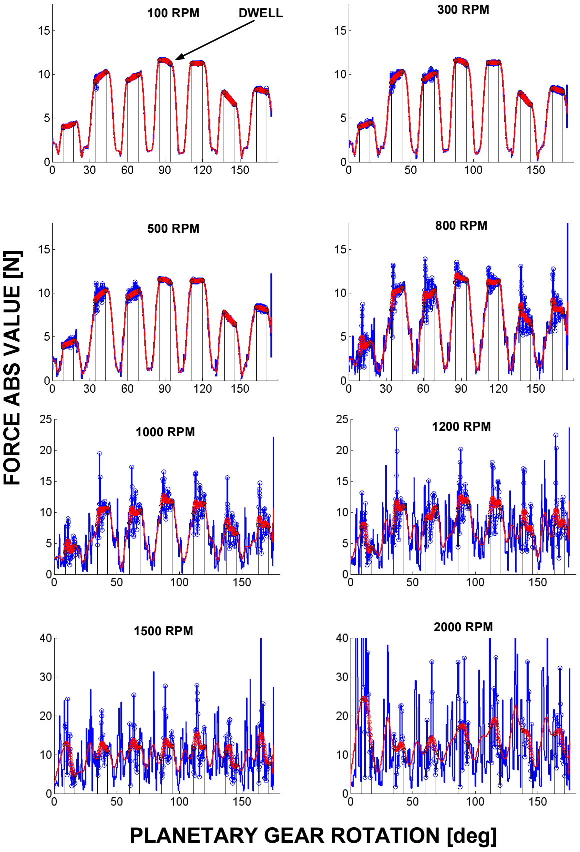

Figure 4: force signals raw (blue) and filtered (red) for different trials at different angular speed of the mechanism. The force peaks (y-axis) represent the restoring force of the springs during the dwells of the cam while rotating; on the x-axis is indicated the angular rotation of the gear head. As clearly shown from increasing the angular speed a vibrational noise emerges affecting the measurement.

The resulting stiffness calculation will be more or less accurate depending on the efficacy of data filtering, in fact from figure 5 emerges that the two-dimensional stiffness measurements are not acceptable for rotational regimes up to 1200 RPM; at this high speed despite the data (red points) result more spread out, the interpolating ellipse preserves a shape comparable with those for obtained at lower speeds, whereas for higher value (1500-2000 RPM) the stiffness calculation is dramatically jeopardized by mechanical noise. In order to perform measurement on humans, it is crucial to obtain at the minimum time execution at which the device can measure two-dimensional stiffness. Past works referred to an 8-10 mm single directional perturbation of 300 ms duration; in our method the device must space 7 different directions in the shortest time as possible maintaining an acceptable level of accuracy and repeatability. It is important to point that the above described test has been performed using a mechanical setup with springs and no damper or absorbing elements which could limit vibrations; contrarily the device was conceived and developed for experiments on humans, where biological tissues result in different stiffness than the one simulated by the previous setup and muscular viscosity plays a considerable counterpart in limiting or even extinguishing any vibrational phenomenon.

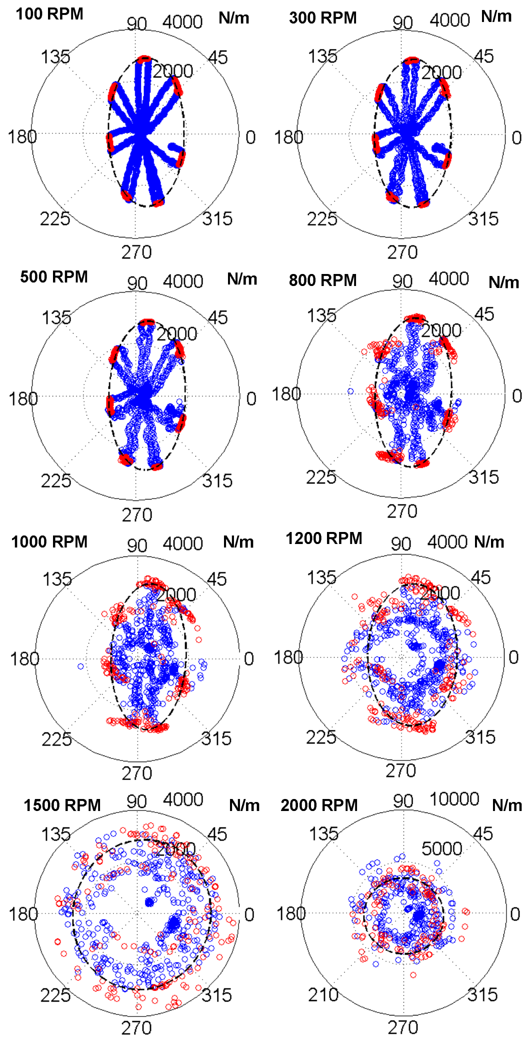

Figure 5: visualization of planar stiffness measurement over the different directions of perturbation executed in one single trial at different rotational speeds. The red points correspond to the values of the restoring forces of the spring during the dwell of the cam, while the blue dots are the force values during the raising and the fall.

## IV. DISCUSSION

The present paper proposes a new solution for the estimation of end point stiffness by decreasing the computational burden by means of a novel mechatronic device. Previous works have been mainly focused on suggesting methodological approaches which are valid and robust, but the efforts on designing hardware solutions are still missing. Most of the studies on stiffness evaluation used planar manipulanda, relying on their high backdrivability and position accuracy. Despite these important characteristics they have limited position bandwidth due to their mass and motor inertia that must satisfy specific requirements for the haptic rendering. The need of having a modular system that can be mounted on the end-effector of such planar device, and completely uncoupled from the implementation of control schemes driving the robot, may be a valid alternative for studying arm characteristic while manipulation tasks. Of course such kind of device using multiple cyclic perturbations has its limits; a fast multidirectional measurement leads to vibrations and noise that may affect the measure and execution time could be too long to avoid stretch reflex and voluntary contraction. Despite all we think that improvements in the system design can lead to much more accurate and reliable experimental results. We aim to focus the measurement on the stiffness counterpart of the arm impedance but a new mechanical design refinement is already ongoing and will allow estimating all the components of muscular activity. The main purpose is using the method proposed by Perrault et al. [13] consisting on perturbation to estimate impedance in a very short time (less than 0.5 s) using the proposed device mounted on a planar manipulandum currently used in our laboratory[19].

This method is in contrast to the standard steady-state methodology discussed in the introduction of the present work, that requires different trials (trajectories in a reaching task) to measure impedance with the additional uncertainty associated to trial-to-trial variability in subjects' performance. Besides estimation of impedance by using steady-state method requires that the subject does not intervene when the step perturbation is superimposed, and it is difficult to detect voluntary reactions which may strongly affect the measures. Due to the design and simplicity of the proposed device (1DoF) our purpose is succeed in generating unpredictable perturbation in a time short enough to anticipate the voluntary reaction. Once the system is mounted on a planar manipulandum hopefully it will be possible to study force field adaptation paradigms and at the same time without any additional algorithm to use the device in order to obtain a real time reading of the impedance modulation while performing different tasks in simulated environments.

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