Effect of Homogenous Object Stiffness on Tri-digit Grasp Properties

Sasha B Godfrey[1], Alessandro Altobelli[1,2], Matteo Rossi[1,2], and Antonio Bicchi[1,2]

***Abstract*—This paper presents experimental findings on how humans modulate their muscle activity while grasping objects of varying levels of compliance. We hypothesize that one of the key abilities that allows humans to successfully cope with uncertainties while grasping compliant objects is the ability to modulate muscle activity to control both grasp force and stiffness in a way that is coherent with the task. To that end, subjects were recruited to perform a grasp and lift task with a tripod-grasp device with contact surfaces of variable compliance. Subjects performed the task under four different compliance conditions while surface EMG from the main finger flexor and extensor muscles was recorded along with force and torque data at the contact points. Significant increases in the extensor muscle (the antagonist in the task) and co-contraction levels were found with increasing compliance at the contact points. These results suggest that the motor system may employ a strategy of increasing co-contraction, and thereby stiffness, to counteract the decreased stability in grasping compliant objects. Future experiments will examine the extent to which this phenomenon is also related to specific task features, such as precision versus power grasp and object weight.**

***Index Terms*—EMG, Grasp, Robotics**

I. INTRODUCTION

Multi-finger grasp is a complex task that is normally performed by humans without any effort. When grasping and lifting an object, the constraint on the grip force (normal to the surface of the object) is unilateral: it must exceed a value that depends on the weight of the object (load force) and on the friction coefficient between the fingertips and the object. Due to the minimal constraints and redundancy within the human motor system, the problem of choosing the correct grip posture and force can potentially have an infinite number of solutions. Understanding the way in which the central nervous system (CNS) regulates the force during the grasping and lifting phase of an object is therefore not simple but of primary importance. Several studies [1], [2], [3] have shown that the CNS makes use of specific patterns of co-activation of muscles to grasp an object. He et al. [4] for example suggested that the coordination of multiple hand muscles seems to be invariant across different grasp forces and different contraction history profiles.

Undoubtedly, human motor control could be affected by several factors as it performs a grasping task. In [5], [6], [7] the authors investigated the effects due to the geometry, the friction, and the weight of the grasped object on the value of grip forces and load forces. Another important property that can influence the contact force distribution is the object compliance: compared with rigid objects, compliant objects present additional uncertainties and Winges et al. [8] showed that, during a grasp, when one or two contact points are compliant, the activation patterns of finger muscles are different with respect to the case where the contact points are rigid. Besides analyzing the grip forces, to fully understand the control of hand grasping by the CNS, it is important to study how the hand stiffness is regulated during a grasp: stiffening behavior is commonly realized to stabilize movement or to fix posture in isometric tasks [9] and recent findings suggest that, to some extent, grip stiffness is independent from grip force [10].

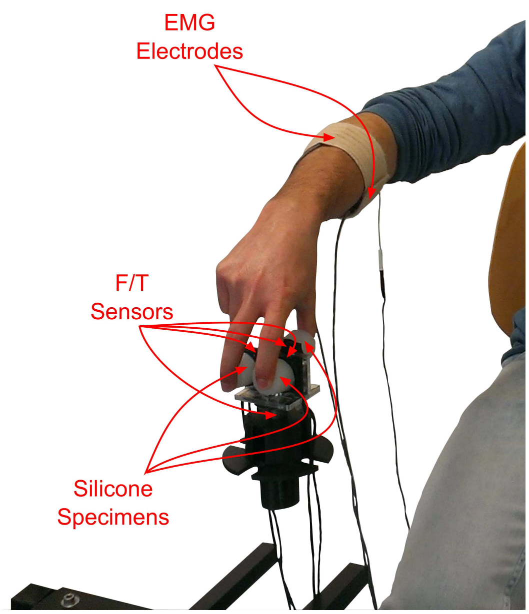


Fig. 1: Experimental setup used for the trials.

In this paper we investigate the relation between object compliance and grasping stiffness of the hand. To achieve this goal, we conducted experiments with 11 subjects using the Tripod Device: an instrumented manipulandum that can be grasped with three fingers and includes three modular contact surfaces. Each contact surface consists of a contact module characterized by a certain level of stiffness: rigid, high, medium, or low stiffness. The experiment consisted of four blocks of trials, corresponding to the four different levels of stiffness; in each trial the subject grasped and lifted the

[1]All authors are with with the Department of Advanced Robotics (ADVR), Istituto Italiano di Teconlogia, 30 Via Morego, 16163 Genova, Italy. [2]Additionally, A. Altobelli, M. Rossi, and A. Bicchi are with the Centro di Ricerca “E. Piaggio”, Università di Pisa, 1 Largo L. Lazzarino, 56122 Pisa, Italy. {sasha.godfrey, alessandro.altobelli, matteo.rossi, antonio.bicchi} at iit.it

978-1-4244-9270-1/15/$31.00 ©2015 IEEE

Tripod Device 25 times while EMG was recorded from the Flexor Digitorum Superficialis (FDS) and Extensor Digitorum Communis (EDC). These two muscles are the main finger antagonist pair and thus can be used to monitor the EMG activity resulting in the production of grasp force as well as overall hand stiffness; this assumption is in agreement with the capability of the human control system to increase hand stiffness exploiting the co-contraction of antagonist muscles [11].

II. Materials and Methods

A. Study Design

Eleven healthy volunteers participated in this study (5 males and 6 females, mean age 28 $\pm$ 3 years, 10 right-handed). Before starting the study, all participants signed an informed consent previously approved by the regional ethics committee. The study consisted of four blocks of 25 trials each in which the subject grasped and lifted the Tripod Device while EMG was recorded from the main finger flexor and extensor muscles. The device was held steady for a brief period and placed back on a table. At the contact points for the thumb, index, and middle fingers, an interface of varying rigidity was placed. Three silicone interfaces of compliant, medium, and high stiffness were used as well as a rigid ABS plastic interface covered in a thin film of silicone, to match haptic conditions. The order of the four block conditions was randomized to reduce order and learning effects.

B. Tripod Device and Experimental Setup

The Tripod Device is a custom instrumented manipulandum developed to study three-finger grasps. Several sets of contact modules were designed to allow contact surfaces with different levels of stiffness. Each contact module has an interface engineered in Acrilonitrile-Butadiene-Stirene (ABS) rapid prototyping material to allow them to be rapidly interchanged on the device. The manipulandum is equipped with an internal frame made in aluminum using a CNC (Computer Numerical Control) machine to ensure structural rigidity. A set of cylindrical interfaces in ABS or silicone were integrated with the contact module, each with a different level of stiffness. The silicone was obtained by mixing a given quantity of a commercial bicomponent, room temperature-curing silicone (BJB TC-5005A/B), with different percentage of plasticizer (BJB TC-5005C), acting as a softener. Softener was mixed at a percentage of 45%, 20%, 0% as shown in [12] to obtain three different stiffness levels. A fourth specimen was made only with ABS. The four different contact surfaces have a Young's Modulus of 200 kPa, 500 kPa, 750 kPa and 1.4 GPa and are referred to as low-, medium-, and high-stiffness silicone and rigid ABS conditions, respectively.

The force and torque components applied by each finger are measured by three force-torque sensors (Series Nano 17 by ATI, Apex, NC, USA) fixed below each contact module. The effect of cables and the external wrench are monitored by a fourth F/T sensor (Series Nano 17 by ATI, Apex, NC, USA) placed at the base of the structure. An exploded drawing view of the manipulandum with dimensions can be found in Fig. 2. The total weight of the manipulandum, including the sensor cables was 300 g. The Tripod Device was built to allow an additional component to be attached at the base to easily change the weight of the device; in this experiment, an additional 100 g was used for a total device weight of 400 g. Surface EMG signals on the forearm were measured and amplified with a Delsys-Bagnoli 16 channel system (Delsys Inc.). The data acquisition and synchronization were performed in Simulink (Matlab R2012a) software exploiting the Data Acquisition Toolbox, Instrument Control Toolbox, and Simulink Block for Real Time Execution. Force and torque data from the Tripod Device were collected at 100 Hz, and EMG data at 1 kHz.

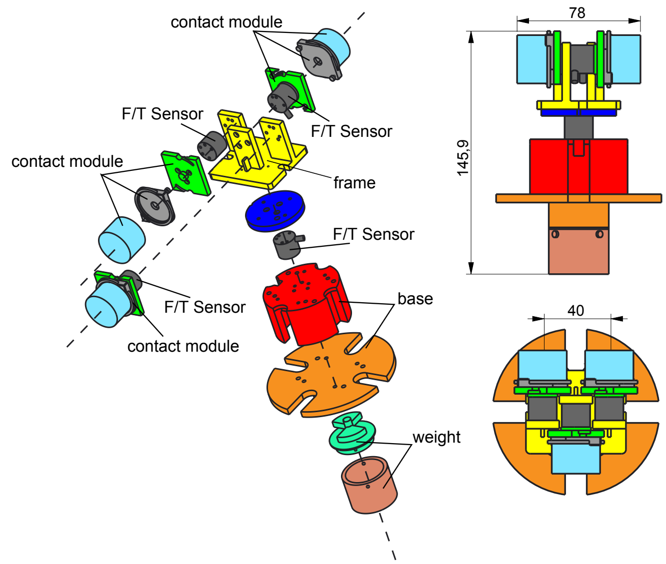
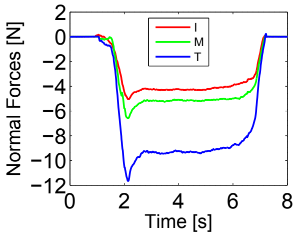


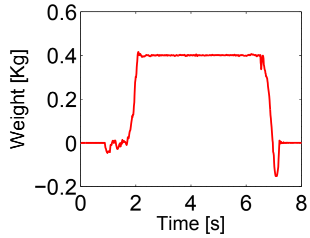
Fig. 2: Exploded drawing view of the Tripod Device and its main features with dimensions in millimeters

C. Protocol

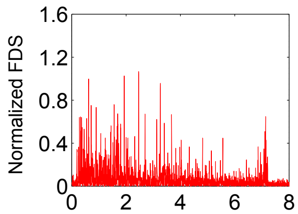
Surface EMG sensors were placed on the main muscle belly of the flexor digitorum superficialis (FDS) and extensor digitorum communis (EDC) muscles following the identification and verification procedures outlined in [13]. Maximum voluntary contractions (MVC) were then collected for each muscle by asking subjects to contract against resistance provided by the experimenter. Subjects were seated in front of the tripod device, which was placed on a table. The device was equipped with the appropriate contact stiffness interface, according to the randomization table. Subjects were instructed to lift the object vertically, avoiding object tilt as much as possible. (Note: in order to encourage as natural a grasp as possible, subjects were given no instruction as to grasp force, eg: to use the minimum force necessary to lift the device.) After a brief (1-2 second) pause, subjects then placed the tripod device back on the table. This procedure was repeated for 25 total lifts. Subjects proceeded at their own pace and were allowed to pause as needed to avoid fatigue both during the block of 25 trials and between blocks. After each block, the interface



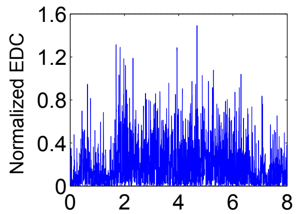
(a) Normal forces exerted by thumb, index and middle fingers



(b) Weight of the object measured by the FT sensor



(c) FDS EMG signal



(d) EDC EMG signal

Fig. 3: An example of the measurements collected in one trial

was changed to a new stiffness condition and a new block of 25 trials conducted until subjects had completed all four conditions.

D. Data Analysis

The first five trials in each block were discarded to avoid learning or crossover effects. The vertical axis of the FT sensor at the base of the manipulandum was used to segment the data into lift, hold, and place phases of the subsequent 20 trials. The mean was subtracted from the EMG data to remove the DC offset before rectifying the data. EMG data was then normalized to the maximum contraction collected prior to the trials. The average value of the hold phase of the EMG and the normal force exerted by each finger was then calculated. The data were further synthesized into an average value for each condition for each subject. To perform group analysis, a repeated measures analysis of variance (RM ANOVA) was used. The RM ANOVA was performed on four sets of data: FDS and EDC EMG levels, co-contraction levels, and the sum of the index and middle finger contact point forces. When a main effect of stiffness was found, the data was then subjected to a post-hoc analysis using Bonferroni corrections for multiple comparisons.

III. Results

All subjects tolerated the protocol well, and each session lasted approximately an hour, including set-up and self-timed breaks. Subjects occasionally reported low levels of fatigue and were encouraged to break as needed to minimize fatigue effects. Measurements from a sample trial are shown in Fig. 3: the normal forces and the weight in Fig. 3a and 3b; the values of the EMG signals in the same time range in Fig. 3c and 3d.

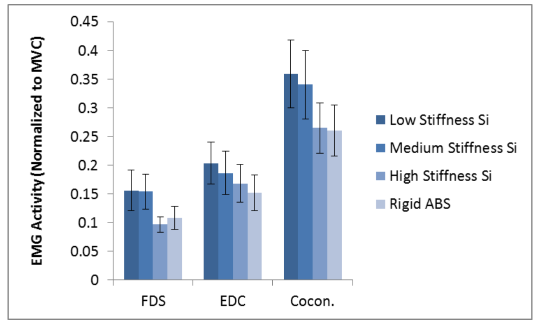


Fig. 4: Average values of FDS, EDC, and co-contraction normalized to MVC, with standard error bars.

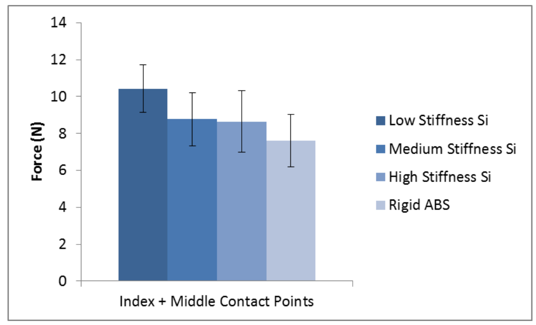


Fig. 5: Average force at the index and middle finger contact points, normalized to MVC, with standard error bars.

A summary of the FDS, EDC, and co-contraction EMG data can be found in Fig 4. The group data was analyzed using RM ANOVA, as detailed in the preceding section. The FDS data violated the assumption of sphericity (using Mauchly's test, $p \ll 0.01$), therefore the Greenhouse-Geisser correction was applied ($\varepsilon = 0.446$). No effect of stiffness condition on FDS contraction levels was found (F=3.592, p=0.071). In contrast, there was a main effect of stiffness condition on EDC contraction (F=9.942, $p \ll 0.01$). This analysis was thus followed by post-hoc tests with Bonferroni corrections: EDC activity during the low-stiffness silicone condition was found to be significantly different from the high-stiffness silicone and rigid ABS conditions (p=0.021 and 0.001, respectively). Finally, the co-contraction values were analyzed: they violated Mauchly's test of sphericity (p=0.006), therefore the Greenhouse-Geisser correction was again applied ($\varepsilon = 0.583$). There was a main effect of stiffness condition (F=6.280, p=0.011) and post-hoc tests showed a significant difference between rigid ABS conditions and low-stiffness as well as medium-stiffness silicone (p=0.045, 0.015, respectively).

To validate the sensor data, the normal force at the thumb contact point was subtracted from the sum at the index and middle finger contact points. The resulting difference was found to be near zero, as expected (data not shown). The average of the sum of the index and finger contact forces is plotted in Fig. 5. The index and middle finger contact force was analyzed using RM ANOVA as before and a main effect of condition was found (F=4.984, p=0.006). However, post-hoc analysis did not find any significant difference between condition pairs, possibly due to the conservative nature of the Bonferroni correction.

IV. Discussion and Conclusions

The study presented above examines the effect of the stiffness of an object on the EMG activity during a grasp and lift task. Eleven subjects participated in the experiment in which they grasped and lifted a tripod object with four different stiffnesses at the contact points. Although subjects generally seemed to exhibit higher FDS activity for more compliant conditions than more rigid conditions, results also showed large intra- and inter-subject variability. There was no significant difference due to stiffness conditions in the FDS activity. The EDC results, however, showed a clearer trend of increasing activity with decreasing stiffness with a significant effect of stiffness. This trend was visible in the post-hoc results showing that grasping and lifting the low-stiffness silicone resulted in significantly higher EDC EMG activity than the two highest stiffness conditions. Finally, there was a main effect of stiffness on co-contraction levels, with post-hoc tests showing EMG co-contraction was significantly lower when grasping and lifting the rigid ABS compared to both the low- and medium-stiffness silicone. Together, these results suggest the co-contraction changes are primarily due to the increased EDC levels rather than a change in FDS levels.

To further understand the meaning of the change in EMG levels, we examined the force produced during each condition. Though there appears to be a trend toward increasing force with decreasing stiffness, and indeed a main effect of stiffness on force levels, post-hoc testing did not reveal any significant differences between specific condition pairs. It is possible that this effect is masked by the conservative nature of the Bonferroni correction. Taken in combination, these results suggest that the motor system responds to the increase in compliance by increasing the activity of the antagonist muscle, ultimately resulting in higher co-contraction levels from the antagonist pair and an overall stiffening of the hand. This increased stiffness would thus serve to counterbalance the decrease in stability of the grasp caused by the increased compliance at the contact points.

The results shown here suggest a decoupling of flexor and extensor activity with changing object compliance, despite relatively stable grasp posture. As mentioned in the introduction, there is evidence that specific patterns of activation are used in grasp tasks; in the future, the effect of varying compliance without varying position on these patterns could be investigated. Further, it is worth noting that because the Tripod Device was grasped from above with only fingertip contact, subjects may have been more likely to increase stiffness to produce a more secure grasp, especially as the contact compliance increased. In a power or conformal grasp, this stiffness effect may thus be decreased due to the increased positional stability and thus reduced reliance on grasp force and/or stiffness. Future experiments will expand the results described above to examine the effects of contact stiffness on both power and precision grasps.

Acknowledgment

This work is supported in part by the European Research Council under the Advanced Grant SoftHands "A Theory of Soft Synergies for a New Generation of Artificial Hands" no. ERC-291166 and under the EU FP7 project WEARHAP "WEARable HAPtics for Humans and Robots" no. 601165. The authors would also like to acknowledge Dr. Matteo Bianchi for his contribution to the study design and analysis.

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