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FFLS: An accurate linear device for measuring synergistic finger contractions

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***Abstract*— After decades of theoretical study in physiology and neurology communities, the paradigm of muscle synergies is now being explored in rehabilitation robotics as a strategy to control mechanical artifacts with many degrees-of-freedom (DoF) in a simple yet effective and human-like way. In particular, muscle synergies during grasping and in graded-force tasks are of great interest for the control of dexterous hand prostheses.**

To this end, we have designed and tested a novel device to accurately and simultaneously measure fingertip forces. The device, called FFLS (Finger-Force Linear Sensor), measures the forces applied by the human fingertips in both directions (flexion and extension of index, middle, ring and little finger plus thumb rotation and abduction/adduction). It is suited for several different hand sizes, enforces high accuracy in the measurement and its signal is guaranteed to be linear in a high range of forces (100N in both directions for each finger). It outputs six analog voltages (±10V), suited for processing with a DAQ card.

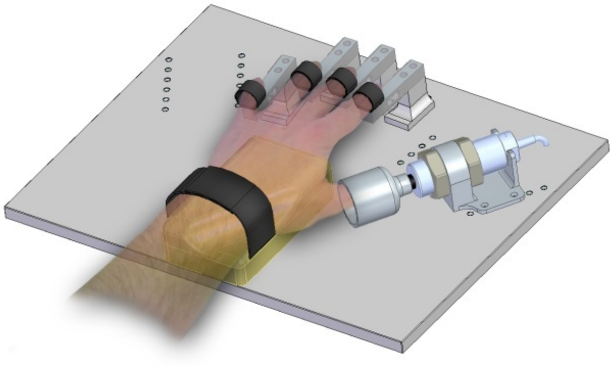

Fig. 1. CAD-rendering of the FFLS, configured for left-hand finger force capturing.

I. INTRODUCTION

From the point of view of control theory and robotics, the dexterity of the human body involves the management of a very high number of degrees-of-freedom (DoFs) and related actuators by the nervous system. The relationship between actuators, which may be identified as the motor units (MUs) and DoFs, is in general not one-to-one: muscles span multiple joints, MUs span several muscles, and the tendon routing is far from simple. Nevertheless, with practice, humans learn to control their body to an astonishing degree of precision.

In order to solve this paradox, a paradigm of muscle synergies [1], [2], [3], [4] has been put forward in the past decades. According to it, muscles (and MUs) are usually activated in a coordinated fashion, so that only a few control signals of the (central) nervous system are required for most every-day tasks. The idea of limiting the number of control signals is now being applied to robotic control and it has promising usage, for instance, in (hand) prosthetics: as multi-fingered prostheses appear on the market and are used in the clinical environment, an increasingly finer control schema is required in order to take full advantage of their dexterity.

In this paper we focus on this problem. Accurately measuring the forces exerted by the fingers simultaneously, and then relating them to muscle-activation detection systems has been an active research topic. Surface electromyography (sEMG) is a particularly prominent technique in which MU activation potentials (MUAPs) are detected. Since MUAPs are related to muscle forces, whether sEMG can be used for force control of an arm-hand mechanical artifact, namely a prosthetic hand, is a fascinating problem. To this end, a device to accurately measure fingertip forces is, as far as we know, still missing.

We hereby describe the FFLS (Finger-Force Linear Sensor), a simple yet extensively developed device which solves this problem. Measuring finger force has been tried before, using wearable fingertip sensors [5], [6], [7], gloves [8] or instrumented graspable objects [9], [10], but most such devices are unidirectional and none of them reach the precision of the FFLS. In particular, the FFLS can accurately and simultaneously measure the force applied by the human fingertips in both directions (flexion and extension of index, middle, ring and little finger plus thumb rotation and abduction/adduction)[1]. It can be easily adapted to several different hand sizes, enforces high measurement accuracy (reaching an overall accuracy of ±0.35% over the nominal measurement range) and is guaranteed to be linear in a high range of forces (100N in both directions for each finger). It outputs six analog voltages in the range of ±10V, suited for processing with a data-acquisition (DAQ) card.

We believe that, using the FFLS, new insight into the actual human finger forces can be obtained, allowing the

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[1] Whereas *thumb rotation* is an intuitive description of the thumb rotational motion, *flexion / extension* of a finger refers to pushing down / pulling up a finger, and *adduction / abduction* of the thumb refers to drawing the thumb closer or further away from the palm.

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muscle synergies to be detected and studied. Using sEMG for instance, the correlation of synergies with muscle activity can be captured, and those forces may be predicted as earlier work seems to indicate [11].

The paper is structured as follows. Sec. II describes the sensor hardware in detail and discusses sensor calibration. In Sec. III a first application of measuring maximum comfortable single finger forces is shown and the experiment results are listed. Finally, Sec. IV summarizes the paper and discusses the future work.

II. HARDWARE DESCRIPTION

A variety of sensor technologies are available to measure (finger) force(s), from a simple threshold–based switch with a discrete 1-bit digital output to large resistive or capacitive tactile sensor matrices (commonly used in robotics). The goal of the sensor in this work is to simultaneously and accurately measure the flexion *and* extension forces of the index, middle, ring and little fingers plus the thumb flexion/extension and adduction/abduction. Strain gauge–based sensors were chosen, commonly used in laboratory and industrial environments, where high accuracy, robustness, repeatability, bipolarity and low hysteresis are important. The strain gauge–based sensors also provide linear output characteristics, making calibration easy and rendering the linearization calculation step with further additive measurement errors unnecessary.

The requirement to accurately capture single finger forces of most adult hands with respect to various hand sizes and the hand used (left or right) necessitated a highly configurable platform for the sensors.

Fig. 1 shows a CAD-rendering of our proposal using four single–axis strain gauge sensors for measuring the finger forces and a single two–axis force sensor for measuring the forces of the thumb. All force sensors are mounted on a sturdy aluminum plate providing a high number of adjustable positions for the sensors. Palm is supported on a CNC-milled wooden plate and direct hand contact to metal (rig and sensors) is avoided to minimize unpleasant thermal conductivity that could possibly alter the finger forces exerted by participants.

The output of each force sensor axis is connected to a dedicated signal amplifier, converting the applied force loading into voltage [Newtons→Voltage]. The analog voltage outputs of the converted force signals are provided on a 68-pin male SCSI connection for direct attachment to numerous industry standard DAQ-cards.

A. Finger force capture

The index, middle, ring and little finger flexion and extension forces are captured using ME-Meßsysteme GmbH KD60-100N industrial strain gauge sensor for each finger, capable of measuring up to ±100N (push/pull). The sensor is very precise and has less than 0.1% linearity error, less than 0.1% hysteresis error and less than 0.1% drift over 30 minutes. The strain gauge bridge output is rated at 0.5mV/V. The KD60 sensors are connected to ME-Meßsysteme GmbH GSV-1L 010/250/2 signal amplifiers with 2mV/V input bridge sensitivity, resulting in ±2.5V output for KD60 ±100N loading. The integrated low–pass filter cutoff (-3dB) frequency of the GSV-1L amplifier is at 250Hz.

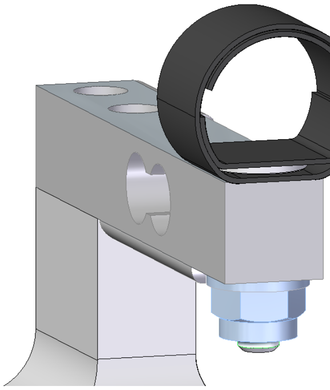

Fig. 2. A close-up showing the adjustable hook-and-loop finger attachment mounted to the industrial strain gauge force sensor. The top of the custom metal M5 bolt is covered with another sheet of hook-and-loop to avoid direct finger–to–metal contact for greater participant comfort.

The fingers are attached to the sensors using adjustable hook-and-loop bands, connected to the strain gauge sensors with a custom bolt [Fig. 2]. This allows a robust connection of differently sized and shaped fingers to sensors with minimal slack.

B. Thumb force capture

Thumb forces are measured across two axes, thumb flexion/extension and thumb adduction/abduction. RFS®150XY-100-8-3[2] radial dual–axis strain gauge sensor from Honigmann Industrielle Elektronik GmbH with ±100N range is used for this purpose. It has the accuracy class of 0.25 with a rated output tolerance of less than 0.2%. Each axis of the RFS®150XY is connected to Tensiotron® TS503 strain gauge amplifier from the same manufacturer, with the accuracy class of 0.1. Nominally, a ±100N loading on the RFS®150XY produces an output of ±10V on the TS503s. The TS503 integrated low–pass filter cutoff (-3dB) frequency is at 55Hz.

Tests revealed difficulties of strapping the thumb to the sensor with hook-and-loop bands and simultaneously avoiding the slack in 2 axes. In FFLS the thumb is instead attached to the 2-axis sensor using an exact gypsum cast that is custom made for each participant and that allows a perfect fit between the thumb and the sensor.

C. Sensor calibration

Sensor calibration is essential for a high quality of measurements. As the strain gauge based–sensors are highly

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[2] *RFS* and *Tensiotron* are registered trademarks of Honigmann Industrielle Elektronik GmbH.

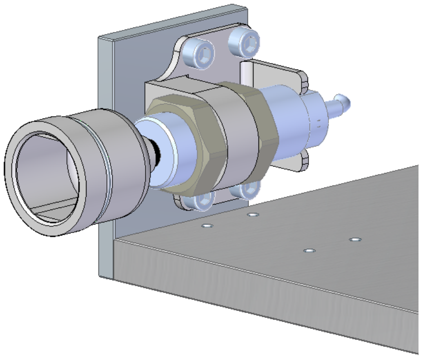

Fig. 3. 2-axis thumb sensor in a 90° rotated position for calibrating the thumb adduction/abduction axis with a calibration mass.

linear, two point calibration is sufficient. First, the zero-point is calibrated (with no external forces applied). GSV-1L strain gauge amplifiers support a digital taring function, triggered with the help of a push-button. 2-axis thumb sensor, connected to dual TS503 amplifiers, must be manually tared using multi-turn trimmers in TS503s, for each axis separately.

The second calibration point is optimally chosen near the end of the measurement range. We used an exact mass of 8.000kg (in an exemplary gravitational field of $9.81m/s^2$, the mass of 8.000kg evaluates to 78.48N). Special positions are available on the baseplate for calibrating the KD60 and RFS® 150XY sensors (also in 90° rotation for the latter [Fig. 3]).

III. APPLICATION

In order to test the effectiveness of the FFLS, we measured the maximum comfortable single finger forces for each finger in both directions, exerted by seven intact human subjects (all right-handed; 5 male, 2 female; age 27.9 ± 5.3yrs, min. 23, max. 39). The subjects sat on an office chair, adjusted for each subject for maximum comfort, keeping the armrest at the same level of the FFLS palmrest. Their right hand fingers were then comfortably tightened to the sensors.

A large monitor displayed the subjects a visual stimulus, consisting of a set of bars dictating the finger and its direction to be actuated [Fig. 4]. The participants were instructed to flex, extend, rotate, adduct or abduct the indicated finger with ”maximum comfortable force”. Each contraction was stimulated once for 5 seconds, and five times for the duration of 2 seconds. Three seconds of rest were allowed between every contraction in the stimuli in order to avoid muscle fatigue. Thus each subject generated 72 contractions, with an approximate duration of 7 minutes. Data from the FFLS was sampled with a 12-bit National Instruments PCMCIA DAQCard-6024E at 250Hz.

Fig. 5 shows an example of the gathered data. Positive values denote extensions while negative values denote flexions. An observation of the graph highlights the higher forces on flexion movement compared to extension. During the experiment, the subjects univocally reported that it was subjectively easier to perform flexions than extensions.

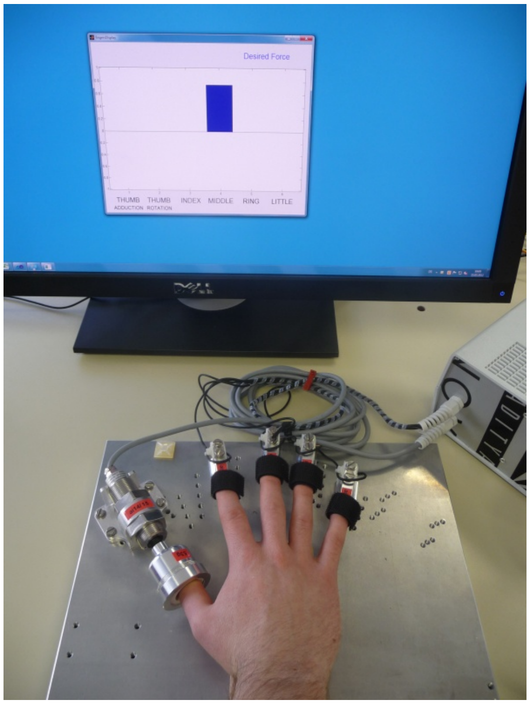

Fig. 4. Experimental setup capturing maximum comfortable forces. Monitor displays visual stimulus, fingers and thumb are attached to FFLS.

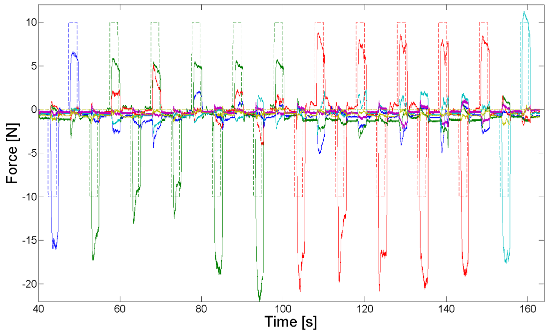

Fig. 5. An excerpt of acquired trial data: ternary stimulus (dashed line) and force values (continuous lines) of the little (blue), ring (green), middle (red) and index (cyan) fingers.

In order to evaluate the average exerted force for each subject and contraction, the raw data were split according to the stimuli; the delay between the stimuli and the force was accounted for, by selecting those samples for which 75% of the force maximum absolute value during the stimulus was reached. The average force over this interval was then evaluated, generating 72 values for each subject.

Table I shows the results for the five repetitions of the 2s sequences (the results obtained for the 5s sequences were found to be not significantly different and thus will not be listed explicitly). As the results show, the middle finger and the thumb produce similar forces during flexion; during extension, the thumb reaches higher values than the index and the middle fingers. Significantly smaller forces are only reached by the ring and the little fingers, especially during extension. All subjects could produce the highest force when adducting the thumb. All this is in agreement with everyday experience, and no sensor limit of the FFLS was ever reached.

Lastly, no subject reported fatigue or discomfort during the experiment.

TABLE I

MAXIMUM FINGER FORCES. MEAN VALUES IN NEWTONS OVER ALL SUBJECTS, PLUS/MINUS ONE STANDARD DEVIATION.

	Flexion	Extension
Index	15.15 ± 4.48	5.67 ± 1.42
Middle	14.99 ± 2.29	5.63 ± 1.76
Ring	13.02 ± 1.66	3.83 ± 1.33
Little	13.20 ± 2.99	3.50 ± 1.31
Thumb	16.12 ± 5.18	8.96 ± 1.27
	Adduction	Abduction
Thumb	20.03 ± 6.73	8.25 ± 3.26

IV. CONCLUSIONS AND FUTURE WORK

In this paper we have introduced the FFLS, a novel strain-gauge-based device capable of accurately measuring fingertip forces. The device measures index, middle, ring and little finger flexion and extension, thumb rotation and thumb adduction/abduction. Adaptable to several different hand sizes, it enforces highly accurate measurements and is linear across a force range of 100N in both directions for each finger (total 200N). The effectiveness of the device was validated by testing it in conditions of maximum force exerted along each finger and direction, and proved to be well within the physiological range. From the measurements in Sec. III/Table I, we concluded that the range of ±100N is too generous. This detail will be improved in the future versions of the device resulting in higher signal-to-noise ratio and greater effective measurement resolution.

Future Work: The FFLS is particularly suited for detection of finger force synergies, that is, coordinated, coherent activations of the fingers, since the signals from the strain gauges are completely independent of one another. This is crucial when sEMG needs to be related to finger forces. Experiments in this field using the FFLS are ongoing at our Institutions, with the final goal of force- or impedance-based control of a dexterous mechanical hand or prosthesis. A preliminary example setup can be seen in Fig. 6, where sEMG electrodes are used to gather MUAPs.

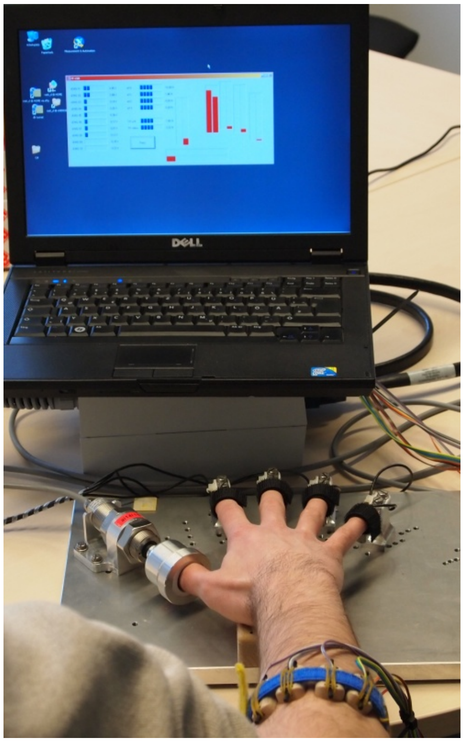

Fig. 6. A preliminary experimental setup employing the FFLS to gather synergistic muscle activations.

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