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Instrumented platform for assessment of isometric hand muscles contractions

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Abstract

Measurement of forces exerted by a human hand while performing common gestures is a highly valuable task for assessment of neurorehabilitation and neurological disorders, but also, for control of movement that could be directly transferred to assistive devices. Even though accurate and selective multi-joint measurement of hand forces is desirable in both clinical and research applications there is no commercially available device able to perform such measurements. Moreover, the custom-made systems used in research commonly impose limitations, such as availability of only single, predefined hand aperture. Furthermore, there is no consensus on design requirements for custom made measurement systems that would enable comparison of results obtained during research or clinical hand function studies. In an attempt to provide a possible solution for a device capable of multi-joint hand forces measurement and disseminate it to the research community, this paper presents the mechanical and electronic design of an instrumented platform for assessment of isometric hand muscles contractions. Some of the key features related to the developed system are: flexibility in placing the hand/fingers, fast and easy hand fitting, adjustability to different lengths, circumferences and postures of the digits, and the possibility to register individual bidirectional forces from the digits and the wrist. The accuracy of isometric force measurements was evaluated in a controlled test with the reference high accuracy force gauge device during which the developed system showed high linearity ($R^2 = 0.9999$). As the more realistic test, the device was evaluated when force was applied to individual sensors but also during the intramuscular electromyography (iEMG) study. The data gathered during the iEMG measurements was thoroughly assessed to obtain three appropriate metrics; the first estimating crosstalk between individual force sensors; the second evaluating agreement between measured forces and forces estimated through iEMG; and the third providing qualitative evaluation of hand force in respect to activations of individual muscle units. The results of these analyses performed on multiple joint forces show agreement with previously published results, but with the difference that in that case, the measurement was performed with a single degree of freedom device.

Keywords: isometric force measurement, hand forces, electromyography, hand control

(Some figures may appear in colour only in the online journal)

Introduction

Quantifying human movements and the associated neural drive behind such movements, is an important goal for neuroscientists, clinicians and bioengineers. Assessment of skeletal muscle function can be used to assess the physiology of the nervous system. In addition, assessment of skeletal muscle function can be used to diagnose neurological disorders, guide neurorehabilitation and motor therapy.

Diseases of the nervous system are often accompanied by changes in motor output in the form of either a reduced output or a complete loss of output resulting in paresis (weakness) or paralysis [1]. Therefore, diagnosis of neurological diseases is possible with the aid of recordings from the output of the nervous system in terms of muscle activation by electromyography (EMG) or by force/torque sensors. Notably, the importance of isometric measurements as an assessment in rehabilitation has been widely demonstrated for several parts of the human body [2, 3].

Among all movements, those of the hand produced by the intrinsic and extrinsic muscles are very difficult to isolate and measure. In fact, with 18 intrinsic and 18 extrinsic muscles and 27 degrees of freedom (DoFs) the hand can perform highly dexterous movements. Hence, designing an ergonomic device that allows the measurement and thus characterisation of these movements represents a truly challenging engineering task. However, with such a device several important theoretical questions could be addressed. For example, it could help to understand how complex movements are generated and controlled by the nervous system, such that they are made with such simplicity and elegance [4, 5]. A second important reason for measuring hand movements together with their neural input relates to the development of human-machine-interfaces for decoding user intentions and controlling advanced hand prostheses [6, 7]. The latter is of special interest for this work.

To date, numerous studies have focused on the development of measurement devices for the evaluation of grip force distributions and digit movements of the hand [8–10]. A device for assessment of hand movement could be based on variety of sensor technologies with the main selection criterion being the kind of movements/contractions of muscles being investigated: i.e. isotonic or isometric contractions. In the first case, the kinematics of the movement contains the important information, given that the muscle length and the associated joint angle change during contraction. Vice-versa, when isometric contractions are studied the force/torque information is the relevant metric. There is a large diversity of commercial and custom made systems for measuring either isotonic or isometric contraction as the design of the system is directed by the number of targeted DoFs and experimental hypothesis. When measuring hand movements associated with isotonic contractions, the commercially available sensors [11–13] and wearable data-gloves with integrated bend sensors [14, 15] provide sufficient information to reconstruct digit and wrist trajectories. Another interesting possibility for assessing isotonic contractions is the estimation of hand and digits orientation and movement using optical or camera systems [16–19]. The majority of devices intended for measurements of isometric conditions rely on strain gauges as their accuracy and size satisfy most of the requirements. Simple devices such as the Jamar hand dynamometer [20], the Martin Vigorimeter [21] and the Harpenden dynamometer [22] may be used to measure the grip force produced by the hand. In addition to these, custom designed devices for measuring isometric finger forces [23–25], grasps [26–28] and wrist forces [29–31], have been developed, however, they can only assess a single degree of freedom or a single joint [32].

Kilbreath *et al* [33] and Radhakrishnan *et al* [34] designed more complex instrumented setups capable to monitor multiple joints in the digits and in the wrist. The former designed a system for the assessment of digital grip forces, whereas the latter focused on the contribution of each phalanx of fingers D2–D5 to the grasping force. However, as both of these devices are designed as grippers they could not measure contractions of finger extensor muscles, hence they could not provide information about synergistic finger extensions which are known to be present during complex actions like precision grasps [35].

To date, the possibility to assess forces by multiple antagonist muscles in complex movement was implemented only in the designs by Westerveld *et al* [36], Castellini *et al* [10, 26, 37], and Reilly and Schieber [38]. Westervald *et al* constructed an aluminium frame in which the arm of the subject could be strapped just proximal to the elbow and wrist joints, while the digits were constrained by preloaded wires connected with load cells. The instrument designed by Castellini *et al* comprises four single–axis strain gauges for measuring the finger forces and a single two–axis force sensor for measuring the forces of the thumb. Similarly, the instrument designed by Reilly and Schieber enables bidirectional finger force measurement via finger rings attached to strain gauges. Although these setups enable the assessment of finger forces in both flexion/extension, they also impose limitations on finger angles during the recordings. This fact is most notable in the system presented by Castellini *et al* where all fingers are fitted at a fully extended position. Furthermore, none of the two systems allow independent assessment of wrist forces which is valuable in general, and specifically in applications such as stroke recovery assessment [39].

Measurement of the hand forces provide important information during basic or clinical studies. However, all custom built devices to measure hand forces lack flexibility in placing the hand/fingers, thus limiting them to specific experimental

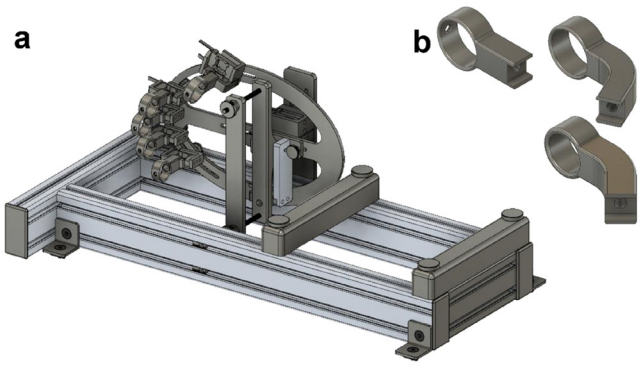

Figure 1. (a) Force measurement platform. Using Knurled screws, it is possible to adjust the positions of key parts without use of any additional tool. (b) The 3D printed finger rings, chosen before fitting the hand in the platform, are removed and fastened using an Allen key.

setups. Furthermore, although multiple devices were presented in scientific papers, repeating findings from said papers is questionable as reproducing the same or similar measurement setups is technically challenging without full mechanical representations.

The aim of this study was to design an adjustable isometric measurement platform intended for the assessment of digit and wrist forces during neurophysiological recordings, specifically during EMG related studies. The design was guided by the requirements of: (i) easy/quick setup, (ii) adjustability to different lengths, circumferences and postures of the digits, and (iii) possibility to register individual forces from the digits and the wrist. These requirements were targeted by limiting the number of independently measured DoFs in the hand. In particular, only one fixing point per digit was included, leading to the measurement of a superimposed force generated by muscles acting on all the phalanges. Thus, the designed system is capable of measuring: (1) DoF forces produced by the fingers (flexion/extension); (2) DoFs forces produced by the thumb (flexion/extension and abduction/adduction) and; (3) DoFs forces produced by the wrist (flexion/extension, radial/ulnar deviation, pronation/supination). The device's ability to accurately and selectively measure hand forces during an EMG recording was evaluated using the data gathered in a fine-wire intramuscular EMG (iEMG) study. Specifically, intramuscular EMG dataset was used for extensive evaluation of the quality of recorded force signals using well-known metrics available from the literature.

Methods

Mechanical design

The mechanical design of the measurement platform was guided by the requirement of developing a highly adjustable device in order to fit different hand sizes and shapes [40], but also to accommodate both left and right hand in a variety of postures during measurements. The platform consists of many parts that can be moved and fastened at a desired position (figure 1(a)). The majority of custom made parts, excluding nuts, bolt and fasteners, are made of aluminium. Connected to a stand, elbow and forearm rests can be adjusted, to accommodate forearms with different lengths, to provide optimal support for the duration of measurements while having an open area over the forearm muscles for placing electrodes. The main measurement console position is also adjustable with respect to the stand. Attached to the console are measurement units which also could be adjusted alongside an oval slit. Each measurement unit is based on strain gauges (S215, Strain Measurement Devices, Bury St Edmunds, UK) and associated signal conditioning circuits (ZSC31050, Integrated Device Technology, San Jose, California, USA). In total, nine force sensors were integrated in the device, one for each finger, two for the thumb and three for the wrist.

A strain gauge housed between the console and the stand measures total force between these parts. This make it possible to register wrist isometric forces in all exerting points including contributions generated at palm and fingers fixing points.

To interface the fingers with the force sensors, finger braces were 3D printed in polylactic acid (PLA). This design allows for accommodation of any finger size into the device at a desired angle during isometric contractions. The exchange of the finger braces is a fast process as each part is fastened using a single bolt. Considering that fingers could be positioned at different angles depending on the shape of the 3D printed finger rings (see figure 1(b)), the exerted force in the cases where angles are greater than zero will not be perpendicular with respect to the strain gauge orientation. This basically means that with bent finger rings, only relative finger forces are being measured. However, this is usually not a problem as the experimental protocol comprises one or several maximal voluntary contractions (MVC) that serve as the reference point which is common protocol in EMG measurements (as in [29]). The wrist is interfaced with the strain-gauge sensors via a padded, comfortable, wrist brace with adjustable width.

Electrical design

The instrumented platform comprises strain gauges, signal conditioning units and a data-acquisition unit (figure 2). The instrumented platform was designed in a way that permits using any EMG device that fits the experiment requirements while keeping the force measurement part unchanged.

Two types of sensor configurations are used in the device, one DoF and two DoF, where one DoF sensors measure forces of index to little finger, two DoF sensors measure forces of thumb flexion-extension and adduction-abduction, and a combined one DoF and two DoF sensor measures the forces generated at the wrist in three DoFs: flexion-extension, pronation-supination and adduction-abduction.

The conditioning electronics circuitry converts deformation of the strain gauge to an analog voltage output in the range of 0–5 V, with the voltage being proportional to the exerted force in the range of ± 100 N which has been reported as maximal finger force in various studies [24, 34, 41, 42]. The sensors were calibrated by the manufacturer in order to have less than

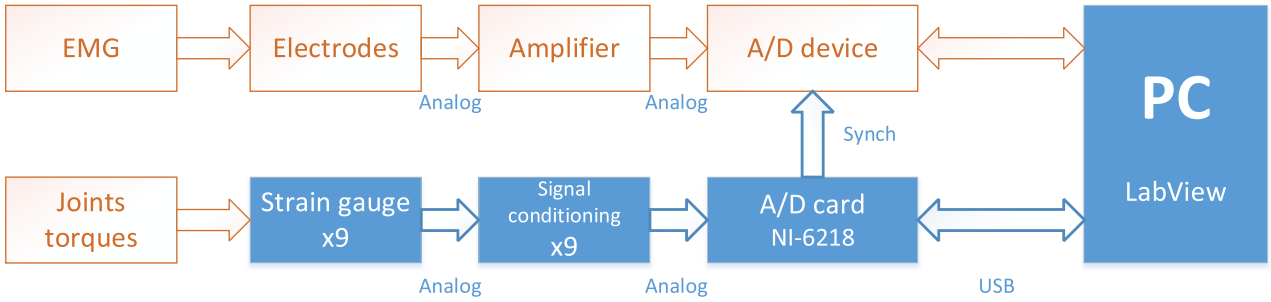

Figure 2. Measurement system overview: top acquisition row shows EMG measurement synchronized with the bottom row measurement of the hand joints torques/forces.

1% full scale error. To decrease sources of electromagnetic interference resulting from e.g. a switching power supply, the signal conditioning electronics were powered using a 7.4 V Li–Po battery. The digitalization of the force signal was done by a data acquisition board (NI-6218, National Instruments, Austin, Texas, USA) connected to a PC. The data was acquired with a resolution of 16-bit and a sampling rate of 200 Hz. The latter was chosen based on the impulse response of the whole measurement chain, including mechanical inertia, which was ~10 ms.

Once embedded in the measurement platform, the force gauges were assessed using a reference force gauge (Mark-10 Series 5 Digital Force Gauge, Mark-10 Corporation, New York, USA). The characterization was performed under controlled conditions, where the reference force gauge was fixed to a moving frame and firmly connected to a sensor on the measurement platform. By manually moving the frame, the strain gauge sensor of the platform was loaded with forces within the common operating range (±60 N). The resulting transfer function between readings of the reference force gauge and the sensor of the instrumented platform showed great linearity throughout the measurement range ($R^2 = 0.9999$, RMSE = 0.010 42 V (0.41 N)).

Due to mechanical construction of the device which comprises multiple sensors connected to the single rigid frame, another test was performed to assess crosstalk between force sensors. This test included interaction with the individual finger and wrist attachment points to mimic isolated isometric contractions of individual hand DoFs. The test was done by selectively pushing and pulling attachments points, one by one, while tracking the sine-wave visual cue presented on the screen. The force was applied by hand to each DoF for 30 s. The Pearson coefficients between individual DoFs are presented in figure 3. Notably increased crosstalk (correlation coefficient 0.3) was observed between thumb flexion-extension sensor and wrist radial-ulnar deviation sensor. This effect is mainly due to the fact that these two movements generate lifting force at the measurement console which is then picked-up at by both sensors. There are also slightly increased correlations between wrist flexion-extension sensor and sensors dedicated to index to little finger (correlation coefficients in range 0.01–0.1). The explanation for this effect lies in similar flexing-extending forces that are elicited on the rigid console by the fingers and the wrist. All other correlation coefficients are below 0.005. All correlations are statistically significant

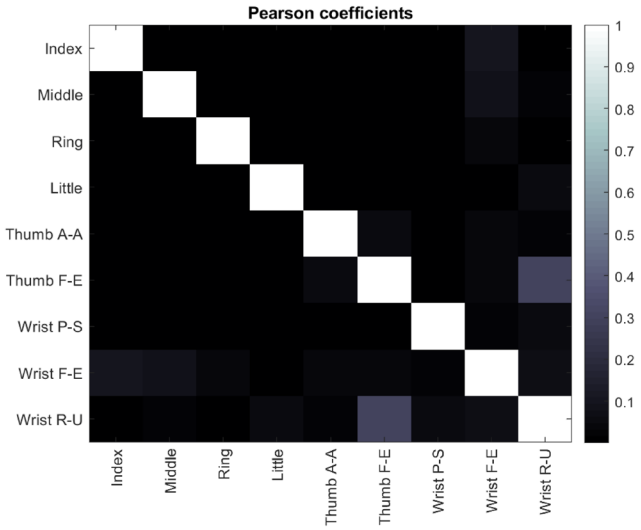

Figure 3. Pearson correlation coefficients between the measurement channels.

at 0.01 level ($p < 0.01$), even after correction for multiple testing (Bonferroni).

Representative experimental assessment

Fourteen male volunteers, aged between 33 and 57 years (mean 40 years), took part in a series of intramuscular EMG recordings using the instrumented platform in order to evaluate its performance. The study was conducted in accordance with the declaration of Helsinki and all the subjects signed an informed consent after receiving written and oral information about the study. The study was approved by the Regional Ethical Review Board in Lund, Sweden.

Before the recordings, the appropriate finger braces with the desired angles were chosen. In this study, finger braces for fingers D2–D5 with 45° curvatures were selected, while the thumb brace was straight. The positions of individual strain gauges were adjusted by sliding and rotating along the oval slit in the platform to produce a natural and comfortable spread of the fingers. During the fitting, the height of the chair was also adjusted so that the arm could be fully rested on the device without additional effort involving muscles in the upper arm and shoulder. The next step in the setup procedure was adjusting the support for the elbow and forearm by sliding them alongside the stand. The final positions should allow the

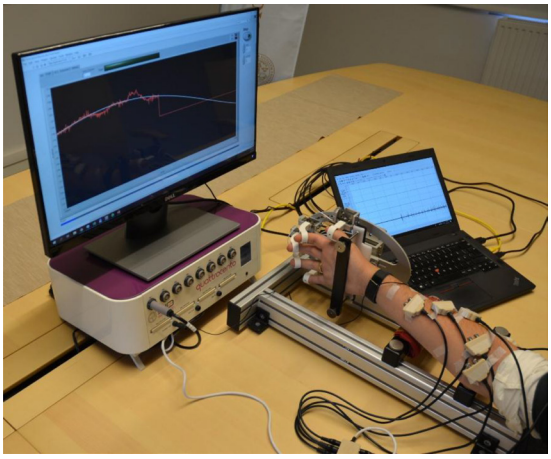

Figure 4. iEMG study set-up using the isometric force measurement platform. The display in front of the participant shows iEMG tracking task with forces exerted on distal phalanges, At the same time iEMG signals were monitored on a separate screen.

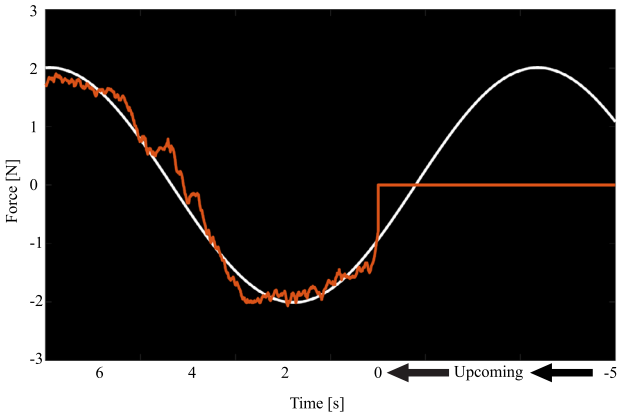

Figure 5. Screenshot of the sinewave tracking protocol. The white line represents tracking cue (sinewave with 0.1 Hz frequency) while the red line represents force level of a single DoF, in this case ring finger (D4) force. The visualization of the exerted force is delayed/shifted for 5 s on the plotting screen that scrolls from right to left. This was done so that the subject can observe upcoming tracking cue trend and be alerted of the upcoming increase/decrease of the target force.

study subject to rest the forearm in a comfortable and stable way and at the same time allow placement of the EMG electrodes. Adjustment of the forearm support was the final step in the hand placement procedure. The hand fitted and positioned inside the device is shown in figure 4.

Following the setup of the hand, the participants performed a familiarization session lasting ~20 min to become accustomed with the recording software. After the familiarization session the participant removed the hand from the device whereafter a MD specialist in neurophysiology placed six bipolar fine-wire intramuscular electrodes (50 mm, 25 ga needle, Motion Lab Systems, Baton Rouge, LA, USA) in the muscles specified for two sub-protocols:

- Long Stump (LS) protocol included the following muscles: flexor digitorum profundus (FDP), extensor digitorum communis (EDC) and abductor pollicis longus (APL), flexor pollicis longus (FPL), extensor pollicis longus (EPL) and extensor indicis proprius (EIP)
- Short Stump (SS) protocol included the following muscles: flexor carpi radialis (FCR), extensor carpi radialis longus (ECRL), pronator teres (PT), flexor digitorum profundus (FDP), extensor digitorum communis (EDC) and abductor pollicis longus (APL)

The muscles were located through palpation and the insertion of the electrodes was monitored and guided using the iEMG signals. For the purpose of real-time monitoring and recording of iEMG, the OT Bioelettronica Quattrocento (OT Bioelettronica, Turin, Italy) with bipolar pre-amplifiers was used. Electrodes were repositioned if the signal quality was not at the satisfactory level which was evaluated by the specialist in neurophysiology. The placement of the six intramuscular electrodes took between 20 and 30 min. When the electrodes were in place and the electrode wires secured with tape to the skin, the participants placed the hand back into the measurement platform. The measurement protocol was designed in an automated manner incorporating strict timings of the movement cues. With the guidance of the onscreen experimental flow control, the subjects performed the following isometric muscle contractions (IMC) with each finger:

- Maximal voluntary finger flexion: The visual and auditory cue marked the onset of the IMC which lasted for 5 s. The end of the IMC was signaled with the visual cue followed by a 5 s rest period.
- Maximal voluntary finger extension: The experimental procedure was the same as for the maximal voluntary flexion.
- Sinewave tracking: the automated protocol generated a sinewave with an amplitude equal to 20% of combined maximal voluntary finger flexion and extension and frequency of 0.1 Hz. This phase of the protocol lasted for ten full periods of the sinewave. During the execution of IMC-s, the participant was shown the tracking cue in form of a scrolling sinewave together with the actual force generated by the targeted finger drawn over the cue (see figure 5, tracking cue in white, actual force in red).

The experimental protocol for thumb and wrist DoFs was the same with the only difference that it included flexion/extension and adduction/abduction of the thumb and flexion/extension and pronation/supination of the wrist.

The fitting time was less than 10 min in all cases, and the complete recording protocol lasted 30 min and was repeated two times for each subject.

Evaluation based on clinical study

The recorded dataset was processed in order to extract three metrics which were used for evaluation of the measurement platform to selectively and accurately measure hand forces. The first metric chosen for this task was the correlation between signals from the different strain gauges, while two other metrics were obtained from a study that addressed the topic of computing force estimates using iEMG signals

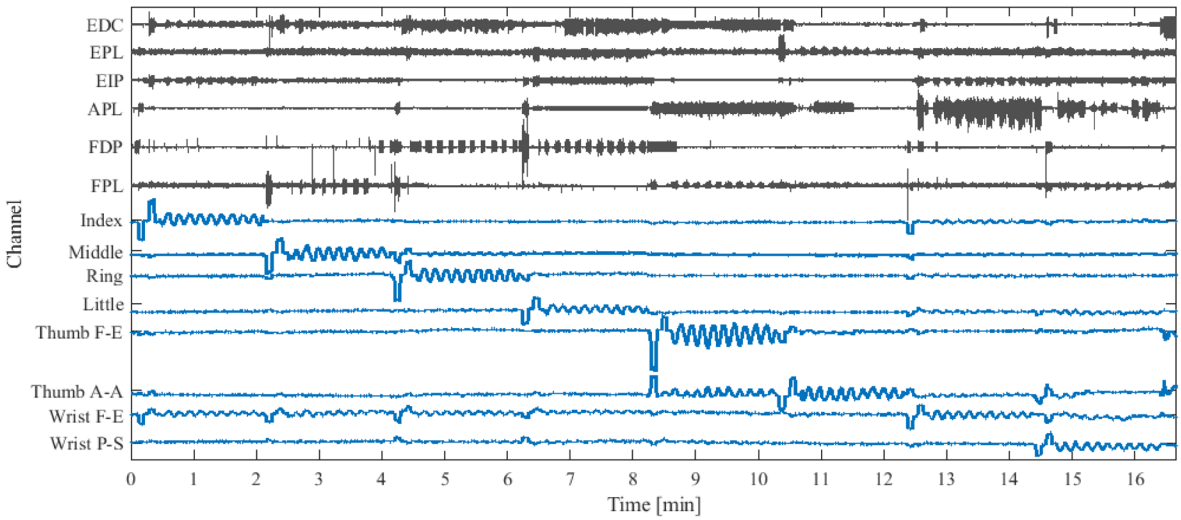

Figure 6. Sample of recorded data during the experimental task. Starting from top to bottom: 1–6. iEMG channels (extensor digitorum communis, extensor pollicis longus, extensor indicis proprius, abductor pollicis longus, flexor digitorum profundus and flexor pollicis longus), 7–14 Strain gauges' outputs. The recording comprises movements of the individual degrees of freedom of the hand in cue tracking sequences.

and comparing them to a force measured using the hand grip dynamometer [43]. Instead of evaluating the iEMG processing techniques, two later methods were used in the present study in a reverse manner to evaluate the force measurement device.

The first metric focused only on the forces captured by the gauges during the execution of the experimental task. This metric aimed at assessing if there was significant crosstalk between recorded channels due to the mechanical construction of the force measurement device. Hence the Pearson correlation was calculated between the force channels (nine channels) of the whole database (14 datasets).

The second metric was a force estimation method taken from [43]. The method was implemented as a Matlab 2018b (MathWorks, Inc., Natick, MA, USA) script. The iEMG channels were paired with the appropriate force channels: FDP and EDC with a gauge on D2-5; FCR and ECRL with the wrist flexion-extension force gauge, APL with thumb abduction-adduction gauge and PT with the wrist pronation-supination gauge. The pairing was done in respect to highest signal-to-noise ratio of an iEMG channel within a single tracking task done by a finger or wrist. The motor units' action potentials (MUAP) with an amplitude larger than 95th percentile of the input signal amplitude distribution were extracted and represented with the discrete markers. A moving average filter was applied over the extracted markers in order to obtain a short-time estimate of the discharge rate of the active motor units. The window width was set to 600 ms as this has been indicated as optimal in previous studies [43]. As the last step, the force estimate was normalized between 0 and 1. In addition, the measured force on each channel was divided into two domains corresponding to antagonistic forces: flexion-extension, abduction-adduction and pronation-supination. This way, an estimated force which occurs only when a muscle is active was correlated with the measured force of the same phase, while opposite phase was set to 0. In accordance with previous study on which we based this metric [43], the correlation between the estimated and the measured force was selected as relevant and the Pearson and Spearman coefficients were used for quantification.

The third evaluation metric was based on full decomposition of iEMG signal which extracts individual MUAP-s [43]. In the case of this iEMG signal, the decomposition algorithm identified seven muscle units which is comparable with previous studies [43]. The calculation was performed in EMGLAB, a program developed for Matlab [44].

Results

The device was successfully used in all of the measurement sessions without any adverse events. Sample signals of a volunteer performing the abovementioned experimental protocol are shown in figure 6.

Results of the first evaluation metric (correlation between strain gauge channels) are shown in figure 7. The Pearson coefficients reveal increased correlation between neighboring digits (coefficients between 0.2 and 0.37) which could be expected, and forces of the fingers and wrist flexion-extension force (coefficients between 0.27 and 0.39) which is also expected. All correlations except one (subject 10, ring finger and thumb flexion-extension sensors) are statistically significant at 0.01 level ($p < 0.01$), even after correction for multiple testing (Bonferroni).

The second evaluation metric was based on signal pairs (iEMG andforce). An example of this metric for an electrode positioned within the FDP muscle and the ring digit force is shown in figure 8(a). As described in the previous section, the first computational step was to separate only positive values of the ring digit force (flexion force) while truncating the negative force values to 0 (extension force). As in the case of estimated force, after removing opposite force phase, the measured force was also normalized between 0 and 1.

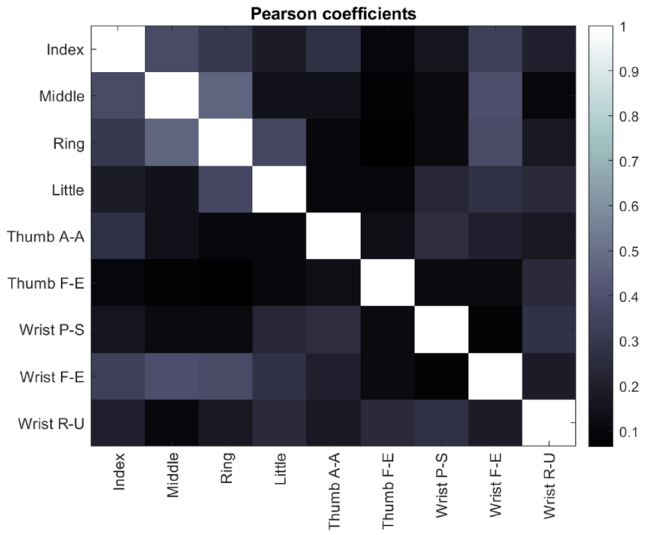

Figure 7. Pearson correlation coefficients between the measurement channels. Increased correlations between force channels are displayed with brighter color.

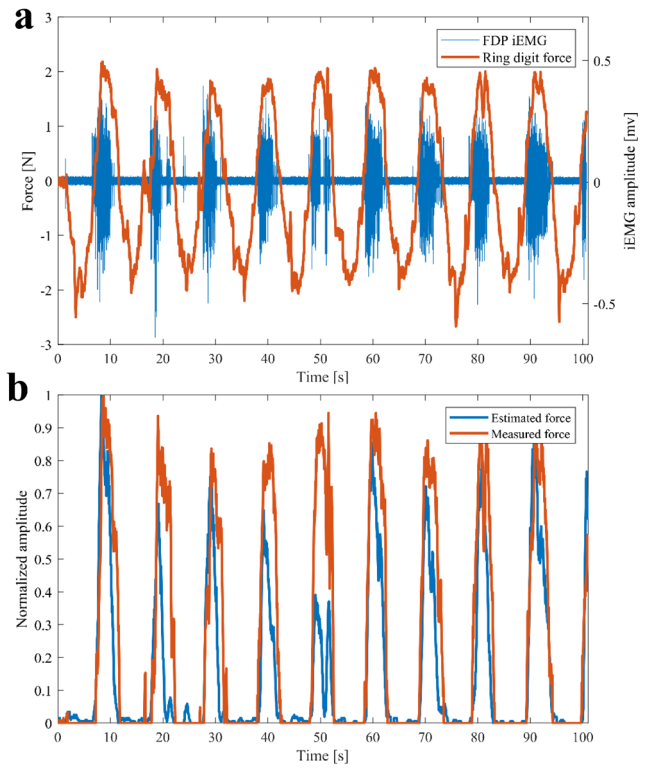

Figure 8. (a) FDP activation during movement of the ring finger. Note that the force sensor voltage output is flipped around neutral level for the consistency with the following figures. (b) The force estimation method taken from [43] alongside only positive values of the ringer forces (flexions).

Figure 8(b) shows estimated force using the method from [43] and measured force after the aforementioned processing.

Median value of the calculated Pearson and Spearman coefficients for all subjects and all iEMG channels (fingers and wrist) were 0.82 (Q1: 0.68, Q3: 0.91) and 0.84 (Q1: 0.71, Q3: 0.89) which is comparable with previously described results [43] for the low elicited force.

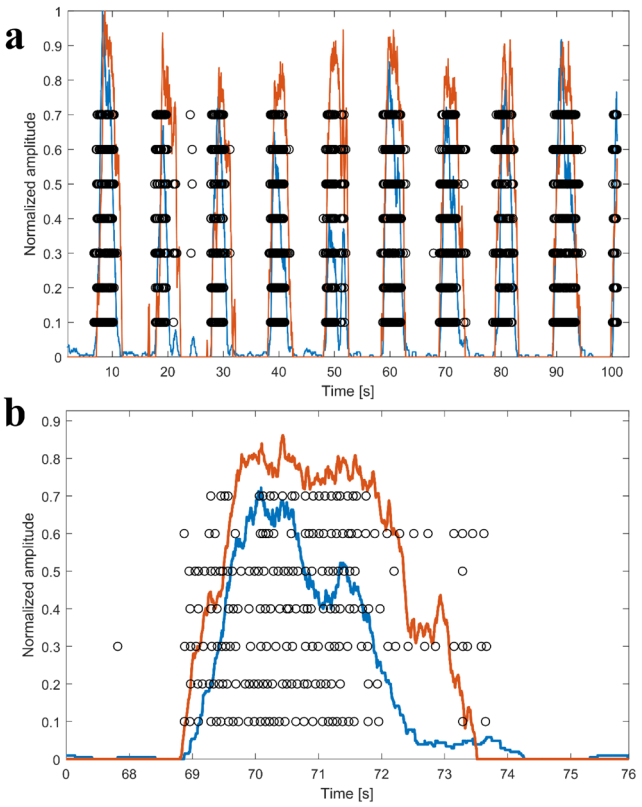

Figure 9. The recruitment and firing pattern of motor units. Each circular marker represents a MU action potential. The algorithm for MU action potentials decomposition found seven distinctive MU patterns The upper figure (a) shows one sine tracking task while the bottom figure (b) shows only single contraction.

Finally, the third evaluation metric was only analyzed qualitatively in case-by-case bases. The results of the decomposition show that there was temporal synchronization between firings of individual motor units and the force onset, and also between the motor unit recruitment and the force level. Example of such procedure for the same iEMG signal as in the second metric is shown in figure 9.

Discussion

With the introduction of more advanced technologies focused on an intimate interaction between man and machine, it has become evident that it is necessary to accurately measure the human way of interacting with the surroundings and copy it to assistive devices. In particular, for making intuitive control algorithms for dexterous prosthetic hands it is of utmost importance to establish computational estimates of the relation between EMG signals, which are commonly used to control prosthetic devices, and the forces exerted by the hand. In current clinical neurology practice and in research, the Jamar, Martin or Grippit, and B&L pinch gauge are used to assess function in muscles acting on the hand. However, compared to the normal hand function these test instruments oversimplified grip patterns. The instrumented platform presented in this paper can measure all finger extension and flexion forces in an objective and repeatable manner. Furthermore, the described

platform comes in a modular design which enables assessment of versatile isometric tasks in the left or right hand, in a wide range of hand sizes and, what is most important, enables setting finger angles between 0° (fingers straight) and 90° (bent) during the experiment.

Besides the mechanical aspects, the paper presents an evaluation of the sensor of the system. As expected, the accuracy of the strain gauges, when tested in controlled settings using a reference force gauge, proved to be extremely high. To evaluate the influence of the mechanical design on the ability of the device to independently measure individual hand DoFs, the crosstalk between force channels was also measured in a controlled manner. During the test, each sensor was individually pulled/pushed by hand with the onscreen force feedback while tracking the visual cue. The main concern that motivated this test was that there could be correlations between force channels due to the fact that multiple sensors were attached to the same rigid body, e.g. two DoF sensors. The test revealed that there is an increased correlation present between sensor dedicated to thumb flexion-extension and wrist radial-ulnar deviation, both generating vertical forces on the main console. It should be noted that noted that force applied on the thumb attachment point is also measurable with wrist sensor, but not vice versa. This characteristic enables easy decoupling of those forces in an online or offline manner.

However, as the system as a whole was designed for capturing elaborate hand forces (multiple DoFs) through a relatively simple interface, the performance of the measurement system was also evaluated in an actual study of intramuscular EMG using well-known metrics. While the test results are comparable with previous studies [43], the device presented in this paper is highly adjustable allowing the positioning of a hand in different postures, which distinguishes it from similar devices presented in scientific publications [34, 36, 37]. With all aforementioned tests carried out, it can be concluded that the instrument platform enables high-quality recordings of finger and wrist forces during on its own and in conjunction with EMG acquisition. Having this in mind, the authors are willing to share full design blueprints of the device, including software used in the EMG study, in an attempt to make comparable or even standardize recordings undertaken in similar neurophysiological studies. The files required to reproduce the measurement device are publically available under MIT license on the GitHub repository:

https://github.com/Nebojsa44/Instrumented-platform

Even though this device has been used mainly for EMG experiments, it can be useful in several other experimental and clinical conditions. For example, the device could be used to monitor progress in rehabilitation after hand or wrist injury or surgery, or after stroke.

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