Measuring Muscle Activation with the HRX-1 Wrist Manipulation Robot

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***Abstract*— A portable robotic system, such as the HRX-1 robot designed for neuromechanics and rehabilitation research, enables motor assessment and training across diverse settings including clinics, laboratories, and home environments. This study presents the findings of wrist muscle activation measurements conducted using the HRX-1 robot in conjunction with surface electromyography (sEMG) electrodes on a cohort of fifteen healthy participants. Participants were seated and instructed to resist and maintain wrist flexion and extension against torques applied to their hand by the robot. Muscle activation data were recorded using two 32-channel high-density surface EMG electrodes placed on the forearm to capture activity from the flexor and extensor muscle groups. The analysis focuses on identifying the number of active regions within the recorded muscle activations under each experimental condition. As expected, flexor muscles were most active during wrist flexion and extensor muscles were most active during wrist extension. There was also no statistically significant change in the number of muscle regions active when torque was increased in each configuration.**

Fig. 1: The prototype 1-DoF joint manipulation robot

I. Introduction

A key effect of musculoskeletal (MSK) trauma and neurological illness is the loss of reliable upper limb function which can have a devastating impact on patients' quality of life. Grasping and manipulating everyday objects is made much more difficult by low muscle power, tremors, spasticity, unilateral weakness and low range of movement. Approximately 5% of the global population experience lasting loss of upper limb function due to stroke [1], while the prevalence of Parkinson's disease, which increases with age, reaches up to 4.8% in those aged 80 or over [2]. Alongside these serious and prevalent conditions, waiting times for physical therapy are increasing in many major healthcare systems [3] due to increasing patient numbers [4] and reduced gatekeeping via primary care [5], [6], whilst early intensive interventions remain essential to enhancing patient outcomes [7], [8].

Robot-assisted rehabilitation has long been proposed as a solution to many of these challenges [9]. Robots can apply forces and torques to resist and assist users, taking the physical role of a therapist, whilst guiding a patient through exercises either autonomously [10], [11] or under the remote control of a therapist [12], [13]. The ability to provide physical therapy without the need for a therapist to be present allows therapy to take place in non-clinical settings such as patients' homes, driving improved patient engagement [14] and increasing access in remote locations such as low- and middle-income countries that often do not have extensive networks of physical therapists or rehabilitation clinics [15].

Robots used in rehabilitation may take many forms, but have some common requirements in terms of power delivery (at least as much force/torque output as their intended user requires), haptic transparency (reduced friction/inertia when not driven, allowing the user to move freely) and ergonomics (must be comfortable to use, matching the user's biomechanics, range of movement and degrees of freedom). Many rehabilitation robots exist as research prototypes and are targeted at specific joints/body parts and specific conditions. For example, MIT's Skywalker robotic treadmill [16] and Imperial College's Hi5 dual-wrist robot [17] are both high cost, high performance room-scale research setups - ideal for scientific exploration of neuromechanics and robotic rehabil-

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itation strategies, but not at all suitable for quick clinical or research deployment due to their design, mechanical structure and dimensions. More portable and light weight robotic solutions are required for faster and efficient preparation of neuromechanical and motor rehabilitation research. Desktop-scaled hand exercisers can resist the movement of the wrist and fingers [18]; however, the intricate mechanisms required to apply different forces and movements to different fingers would be difficult to maintain in real-world use.

Using interactive robots for physical therapy also raises the possibility of connecting the robot's sensors (i.e. user movement data) to computer games to promote engagement and reduce nonadherence, a serious limitation of traditional physical therapy [19]. This gamified rehabilitation has been demonstrated extensively with stroke patients, and a variety of upper limb exoskeletons [20], resistance machines [21] but also in contexts such as paediatric cerebral palsy [22] and recovery from hand injuries [23].

This paper presents the application of a portable lightweight HRX-1 robot for applying torques to the wrists of healthy human-participants, allowing biosignals such as muscle activation to be measured and studied. The HRX-1 robot's primary function is to generate controlled wrist flexion/extension torque, however compared to other similar devices [17], [24], [25], HRX-1 robot's key advantage is portability and compact design which enables fast integration, easy transportation and deployment. This paper presents the results of muscle activation from fifteen healthy participants which used the HRX-1 robot for wrist flexion and extension tasks. Surface electromyography recordings were analysed to identify number of muscle activation regions.

II. HRX-1 ROBOT DESIGN

There is clearly a need for a high-performance, portable, easily adaptable haptic robot that can be used in a variety of different rehabilitation and research contexts. A 1-DoF torque feedback robot has been designed based on Imperial College's Hi5 wrist manipulation robot [17]. This offers high torque, position and torque sensing and a variety of control modes in a compact robotic platform, whilst also being modifiable to work with a number of other joints. The HRX-1 robot measures approximately $280\times200\times115$ mm when collapsed for transportation, and weighs approximately 4 kg.

The below describes the design and construction of such a robot that can be used in many different scenarios.

A. Mechanical Design of HRX-1 robot

The key requirement of a portable, modular joint manipulation robot is the ability to exert strong, comfortable, measurable and controllable torques on specific joints, while maintaining high backdrivability. To achieve output torques that can be useful in human movement research, the robot is directly driven by the 600W Maxon EC90 series brushless direct current motor. Torque exerted against the robot by the user is measured with a Transducer Techniques TRT-100 torque sensor mounted on a flanged coupling to the motor shaft. This coupling has a large eccentric protrusion shaped

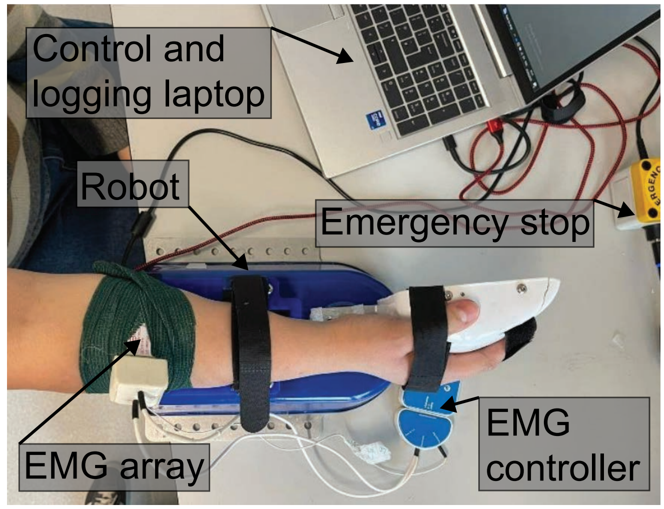

Fig. 2: The experiment setup used to capture s-EMG data of participants using the joint manipulation robot

to interfere with two endstop screws located on a circle around the motor shaft, which can be adjusted depending on the desired range of motion. The handle is mounted to the top side of the torque sensor such that the sensor measures the torque difference between the motor shaft and handle. The handle consists of a thin aluminium frame, ergonomically shaped plastic hand rest (designed for an open palm as this shape is known to minimise contraction in the forearm) and velcro straps to ensure good contact during abduction. The handle is shaped such that for an average-sized hand, the wrist joint will align with the axis of the motor which is essential for safe and comfortable transfer of torque. An arm rest with 8, 80 mm spaced stages of adjustment is mounted on the top of the robot in line with the handle, with more velcro straps to constrain the forearm position and ensure that only the wrist joint is able to move and exert torque against the motor. The robot's key ergonomic features are highlighted in Figure 1.

The need for a portable robot raises the competing goals of low weight and durability. Mechanically, the robot has a steel and aluminium skeleton which secures all load-bearing components, minimizing weight (a low volume of metal overall) whilst maximising rigidity and robustness. This consists of a lower plate to which the motor controller and drive circuit are mounted, and an upper plate which secures the motor and mainboard. Two socket head screws with plastic bumpers are screwed into this top plate, providing range of motion limits that can be adjusted for different users, joints or tasks. Steel supports above the second plate secure a thin, durable plastic cover and the arm rest. This ensures that there is a rigid metal support for the arm, allowing the robot to easily take its weight and keep it in a fixed position relative to the motor.

B. Electronic Configuration

The robot's motion is controlled by a Maxon EPOS4 70/15 controller which offers closed-loop position, velocity and current control, the latter being most useful and most common in rehabilitation, neuromechanics and pHRI (physical human-robot interaction) use cases. The torque sensor output is calibrated and amplified with a Mantracourt ICA2H signal amplifier. This is delivered to the general-purpose analog/digital input/output ports on the controller which can be read by PC-based software, and exposed to other electronic devices/dataloggers via an I/O connector on the back of the robot.

The motor/handle position is read by a Maxon 6400 cpt (counts per turn) encoder which is fixed to the top of the motor. This is again wired to the motor controller and exposed to custom controllers and other hardware via I/O. The robot connects to a computer over USB and is powered by a standard 19.5 V laptop power adapter, both connected to ports on the back of the robot. The power supply can optionally be routed through an emergency stop button which will open the power supply circuit and disengage the motor in the event of a problem.

C. Software Integration and Control System

By default, the robot's onboard motor controller can receive torque output commands from either Maxon's C++ SDK or the EPOS4MATLAB wrapper, allowing the robot to be easily integrated with MATLAB's other scientific computing tools and supported data acquisition hardware. The robot's onboard torque sensor and encoder can also be read in this way, allowing the user's exertion on the handle and joint position to be measured and logged or used in interactive applications. Either method runs over a USB connection to a computer at up to 500 Hz which is sufficient for applications where, for example, the robot needs to produce pre-defined torque curves or impulses, which are common in neuromotor rehabilitation exercises.

III. Electromyography Evaluation of Wrist HRX-1 Robot

To evaluate the robot's ability to exert controllable torque on joints, a user study was performed using surface EMG to measure muscle activation in participants trying to resist the robot's manipulation. Fifteen adult participants were recruited to take part in this study (male and female, ages 20-35). Two participants were left-handed. None self-reported any neurological or musculoskeletal impairment. All participants gave informed consent prior to taking part. The study received ethical approval from the Imperial College Research Ethics Committee with certificate number 21IC6935.

A. Setup

The prototype force feedback robot was placed on a standard-height work desk in front of and to the right of the participant. It was connected to a laptop computer running Windows 10 and MATLAB over USB. Two 32-channel HD surface EMG electrodes (GR10MM0804e electrodes, Sessantaquattro acquisition system, OT Bioelettronica) were attached to the participant's forearm to record flexor and extensor muscle group activation at 2 kHz. The participant's forearm was strapped to the arm rest of the robot, and their hand strapped to the open palm handle. The experiment setup is shown in Figure 2.

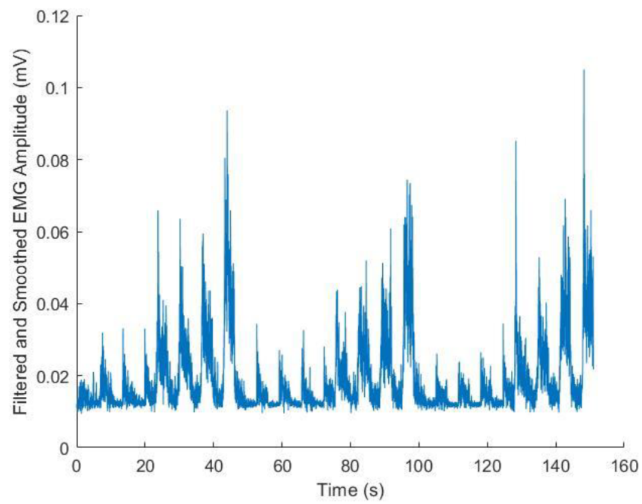

Fig. 3: Sample participant data showing an increasing EMG amplitude during wrist manipulation target tracking tasks at increasing resistance levels

B. Procedure

The initial calibration consisted of three repeats of wrist extension and flexion at a fixed angle of 30° while resisting an increasing torque at four different levels: 0.4 Nm, 0.8 Nm, 1.2 Nm, 1.6 Nm. Each repeat starts off by flexion exercises, holding at each torque level for 3.5 s with 3 s of relaxation between trials to prevent fatigue. After flexion at the highest resistive torque level, the extension trials start (no rest when switching from flexion to extension). Again, wrist extensions are held for 3.5 s at each increasing torque level with 3 s of rest between trials. The rest period is increased to 6.5 s between repeated blocks of trials.

C. Signal Processing and Data Preparation

All data processing has been done in MATLAB. First, a high-pass filter with a passband frequency of 5 Hz is applied on the raw EMG data. Then, outliers are eliminated using a Hampel filter where data points more than two standard deviations away from the local median within a window size of seven are replaced by that local median. At this stage, an envelope filter is applied using the root-mean-square method with a sliding window of 101 data points. The upper envelope signal is what is used for all further investigations. The data was sectioned into trials, separating each trial of each repeat at each torque level and wrist movement. Regional maxima are found by averaging the EMG amplitude recorded by each channel in each of these trials. Heatmaps were created by smoothing and interpolating the data using MATLAB's imresize and imshow commands. The regions corresponding to the top 25% mean EMG amplitude in each case were considered as the number of active regions for that trial.

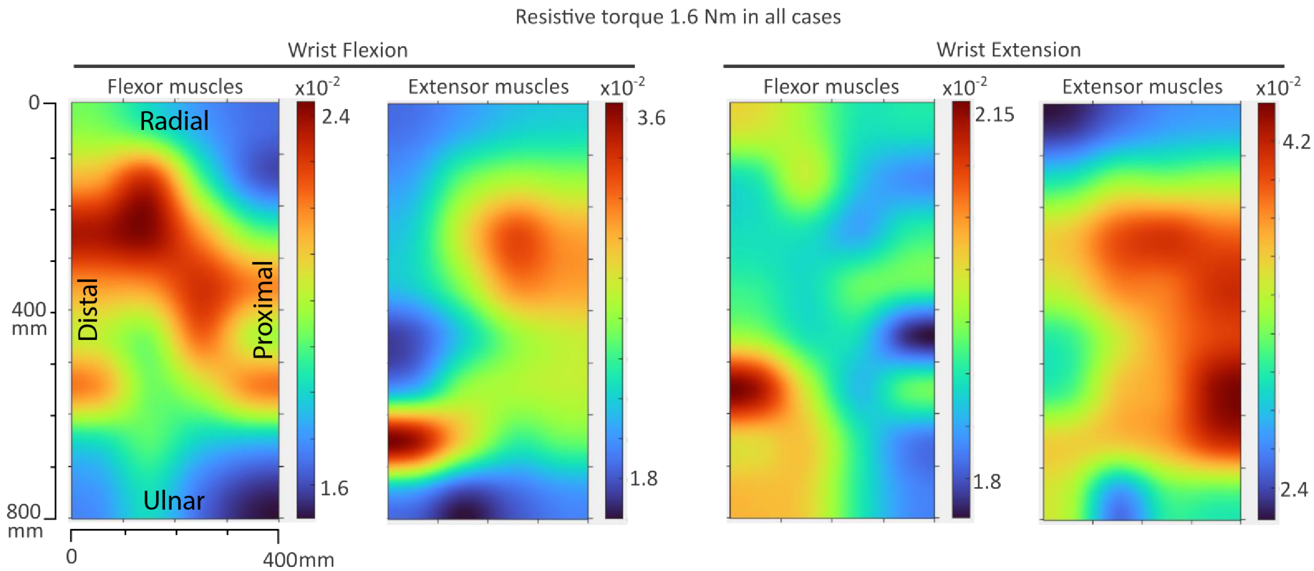

Fig. 4: EMG array heatmaps from electrode arrays positioned across the dorsal (extensor) and ventral (flexor) side of the forearm during wrist flexion and extension tasks

D. Results

Each participant's EMG signal for an active region electrode, after the filtering approach described above, is shown in Figure 3. The main parameter of interest in this study was the average number of active muscle regions when performing the same task at increasing torque levels. The heatmaps of EMG array data and the active region computed are shown in Figures 4 and 5. These heatmaps show that the greatest EMG activity is generated in the flexor muscles during wrist flexion and the extensor muscles during wrist extension. During wrist flexion, the flexor activity is greatest nearest to the elbow (proximal end of the forearm, top of image), suggesting that the flexor carpi muscles that control wrist motion are engaged more than the flexor digitorum muscles that control finger motion. One-way ANOVA tests were performed and there was no statistically significant difference between any of the groups ($p>0.3$ in all cases), showing that the number of active regions does not on average differ when the resistive torque is increased. The results show that the robot targets the wrist muscles specifically and the average number of active regions in the forearm does not increase when the resistive torque is increased, suggesting that the user continues to employ the same motor strategy.

IV. Discussion

The key objectives of the HRX-1 robot are: to be portable, such that it can be easily moved to clinical research sites or patients homes; powerful enough to use for human movement research; and easily connected to other sensors and equipment.

The design of the HRX-1 robot is substantially more compact and lighter than existing comparable systems. For example, whilst the Hi5 bimanual torque feedback robot does not have published size or weight characteristics it is a room-scale device [17], whilst the EDUSA Pro-R (the commercial successor to the IIT WristBot) measures $75\times129\times90$ cm and weighs 65 kg, including a permanently connected computer and display [26]. The smaller size and weight of the HRX-1 means that it can be comfortably carried in a large backpack when walking or cycling, or in hand luggage with most airlines. This supports the robot being used at multiple study locations for clinical or in-home research, as well as used at conferences and exhibitions for live demonstrations of research projects.

Published data on human wrist strength is highly variable, however values up to 12 Nm have been reported for midpronated (neutral) male wrist flexion and extension [27], [28]. Wrist strength in populations with musculoskeletal or neurological illness is known to be substantially lower, with conditions such as stroke reducing wrist flexion/extension torque to values in the range of 2.5 Nm or lower [29], [30], and ageing by up to 40% [31]. Whilst the 4 Nm generated by the HRX-1 would not be able to match or overpower a healthy user's wrist, it can produce meaningful resistance (or assistance) to movement and is well scaled for unwell or aged users. Torque outputs from existing wrist manipulation robots are known to be lower, with the MIT-MANUS having a maximum published 1.43 Nm flexion/extension torque [32] and a more recent, lightweight wrist robot based on twisted string actuation offering up to 2.4 Nm [33]. Recent applications of the HRX-1 robot for combined physical assistance and functional electrical stimulation demonstrated promising results for the robot to be used as a rehabilitation device in clinical settings [34], [35], as well as a research tool for human-robot interaction research [36], [37], [38].

Integration with other sensors is supported by built-in analog and digital input/output connections to the robot

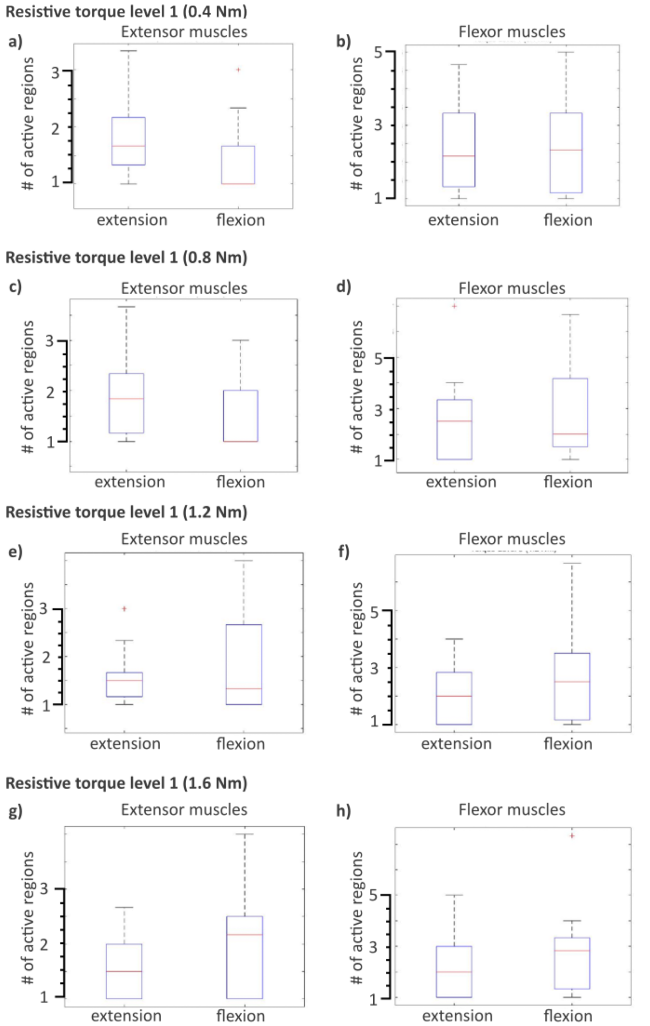

Fig. 5: Boxplots showing the number of identified active EMG regions for extensor and flexor muscles during wrist flexion and extension tasks at increasing levels of torque resistance.

controller, allowing a range of sensors to be directly connected and read. The use of a MATLAB programming environment also allows the robot and more complex PC-connected sensors to be controlled via the same software program, with the option of synchronising datastreams from the robot and sensors in hardware using pulses from the robot's built in input/output. Whilst it would be impossible to achieve compatibility with every possible external sensor, these approaches allow the robot to be used harmoniously with many popular accelerometers, gyroscopes, EMG, EEG, force/torque and pressure sensors.

V. Conclusion

The one-degree-of-freedom wrist manipulation robot presented in this study was evaluated through surface electromyography measurement tasks. The findings demonstrate that the HRX-1 robot satisfies the requirements for a portable, high-performance, and modular torque feedback robotic system. The device successfully generated sufficient torque to support experimental studies involving sEMG recordings in healthy participants.

Integration of the wrist robot with a multi-channel sEMG measurement system provided reliable data acquisition and facilitated research-relevant analyses. Specifically, the system enabled the identification and localization of activation regions corresponding to the extensor and flexor muscle groups during wrist movements.

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