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Wrist and Finger Torque Sensor for the Quantification of Upper Limb Motor Impairments Following Brain Injury

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Abstract

This paper details the design of the Wrist and Finger Torque Sensing module (WFTS): a lightweight, portable device that measures isometric wrist and finger flexion and extension joint torques. The WFTS can be used in combination with rehabilitation robots such as the ACT-3D, with isometric measurement stations, or as a stand-alone device. Because many robotic devices are limited in that they involve the hand in isolation, the WFTS is designed to investigate abnormal joint torque coupling at the paretic wrist and fingers in individuals with adult-onset stroke or childhood hemiplegia during 3D arm movements or isometric generation of shoulder and elbow torques. In short, the versatility of the WFTS allows for a variety of applications.

I. Introduction

In the last decade, many robotic devices have been developed for the paretic hand following stroke. Some aim to assist with rehabilitation or function and others to better quantify the behavior of the paretic hand experimentally. This paper introduces a device, the Wrist and Finger Torque Sensing module (WFTS), that is designed to quantify the behavior of the paretic wrist and fingers during 3D arm movements or isometric generation of shoulder and elbow torques. The WFTS measures isometric wrist and finger flexion and extension torques and can be used in combination with a haptic robot (such as the ACT-3D) or an isometric upper limb joint torque measurement setup.

The loss of independent joint control in the upper limb of individuals with chronic hemiparetic stroke has been quantified under both isometric [1], [2] and dynamic conditions

[3]. The generation of shoulder abduction torque results in coupling of involuntary elbow flexion torque [2] and a reduced capacity for elbow extension torque [4]. This obligatory coupling between shoulder abduction and elbow flexion becomes stronger as the level of shoulder abduction torque increases.

Clinically, it has been observed that wrist and finger flexion is also coupled with shoulder abduction and elbow flexion post-stroke [5], [6]. However, robotic assistive devices, robot-assistive rehabilitation protocols, and experimental studies [7]–[9] have involved or examined the paretic hand most frequently in isolation, with the rest of the upper limb at rest or supported externally. The generalization of these devices and studies to behavior of the paretic hand during shoulder and elbow activation may be limited. For a review of robot-assisted rehabilitation for the hand, please see [10].

In contrast to adult-onset post-stroke hemiplegia, children with hemiplegia exhibit movement disturbances in the upper extremity that have not been extensively quantified, even at the shoulder and elbow. There are many clinical observations of the movement disturbances, and a number of attempts have been made to characterize the behavior of the arm during reaching tasks [11]–[15]. However, the upper extremity discoordination remains poorly understood. More rigid quantification of the behavior of the shoulder, elbow and hand simultaneously may provide important insights.

Recently, we developed a Wrist and Finger Force Sensor module (WFFS) to be used with haptic robotic devices such as the ACT-3D so that isometric wrist, finger, and thumb flexion and extension forces could be measured during 3D limb movements [16] of individuals with adult-onset stroke and children with hemiplegia. Using the WFFS, we were able to provide preliminary evidence with moderately to severely impaired individuals with chronic stroke that involuntary paretic wrist/finger and thumb flexion forces occur during a shoulder flexion and elbow extension task with the limb supported by the ACT-3D. Such involuntary flexion forces were found to increase substantially when shoulder abduction torques were generated simultaneously [16].

These preliminary results support the need for continued rigorous quantification of the behavior of the paretic hand during various shoulder and elbow movements. Such quantification can contribute to better control of robotic devices, to assist with function or aid in rehabilitation. Additionally, it can provide additional information with which to speculate about mechanisms underlying upper limb movement discoordination in adults post-stroke and in children with hemiplegia.

Some limitations of the WFFS were identified during its use in research experiments. The biggest limitation was that wrist and finger (metacarpophalangeal) joint torques were not directly measured. Rather, they were calculated using a combination of finger and thumb length measurements and measured thumb forces, thus introducing potential sources of error. Additionally, because the WFFS was attached to the end of a rigid forearm-hand orthosis, it was not possible to adjust the wrist and finger joint angles without modifications to the orthosis. In light of these limitations, we have developed the WFTS as a more sophisticated update to the WFFS.

II. Design

The Wrist and Finger Torque Sensor (WFTS) module (see Fig. 1) is a lightweight, portable device that measures torques in the wrist joint and the combined torque of the four metacarpal phalangeal (MCP) joints of the fingers of up to 15.5 Nm on each axis. As said, it is a significantly improved version of the earlier WFFS module [16].

The WFTS module can be attached to the rigid forearm orthosis of the ACT-3D robot [3], [17] or used independently in isometric setups such as used in [2], [18] (see Fig. 2). Use of the WFTS in combination with the ACT-3D allows measurement of wrist and finger torques during any of the tasks in its repertoire, including point-to-point or ballistic reaching, work area measurements, limb perturbations, and simultaneous measurement of shoulder and elbow forces and torques. The WFTS could be adapted for use with many upper limb robotic devices with a forearm-hand interface.

A. Mechanics

To accurately measure the net external wrist and finger torques, the WFTS module mirrors the joint configuration of the human hand. The module consists of two mechanisms on two axes (see Fig. 3). The proximal axis needs to be aligned to the human wrist flexion/extension axis and the distal axis to the human metacarpal phalangeal (MCP) flexion/extension axis. The distance between the axes can be adjusted in discrete steps of 10 mm from 60 to 110 mm for use with young children and most adults.

In each mechanism, two independent components hinge on the joint axis of the base element (see Figs. 3 and 4). The first component is an angle adjuster and is fixed to the base element with a bolt. The angle between these can be adjusted in steps of 15° from -60° to $+60^\circ$. The base of the 1-DOF tension-compression force sensor (Omega LC201, $\pm 445 \text{ N}$, Omega Engineering, Stamford, CT) is mounted at the bottom of the angle adjuster.

The second component is the interface box onto which the hand or wrist interface is connected. The box is freely hinged with ball bearings around the joint axis. However, the box is angularly fixed to the load side of the force sensor at the top of the box. The use of a freely hinged component connected to a force sensor on a fixed distance (35 mm) makes it possible to translate the measured forces directly to joint torques (up to 15.5 Nm with the current sensor). It also makes the device insensitive for any torques perpendicular to the joint axis. Those torques are transferred to the fixed world via the ball bearings. This also ensures that the 1-DOF force sensor is loaded correctly, with forces along its primary axis only.

B. Theoretical Analysis

By mirroring the configuration of the human hand, the exact shape and location of the hand-device force interactions become largely irrelevant. This is important, as the distribution of the interaction forces is expected to change with muscle activation. If the distance between the interaction force and the rotation axis changes, it changes for both the human and device joints, thereby canceling out the effect of varying interaction force distribution and location on the torque measurements (see Fig. 5).

C. Hand Interfaces

Multiple hand-palm and finger interfaces, from flat plates to custom-made profiled blocks, have been tested. Some protocols benefit from a lighter orthosis, some from a better fit, others from a higher stiffness. The design of the WFTS module allows for easy switching of these orthoses. With a couple of screws, they can be attached to the sides of the WFTS module. When switching hand sides, the interfaces will also need to be moved to the other side of the module.

III. Performance

A. Calibration

To verify the accuracy of the WFTS module, the device was calibrated using known weights (see Fig. 6). Different weights were placed at a fixed distance from the axis, simulated changes in applied load. To verify that torques around other axes than the joint axis do not influence the measurements, the calibration weights were also placed at several horizontal offset distances in the direction of the axis. The results show that the device responds linearly to the applied torques, but is insensitive to the horizontal offset distance of the applied load. The latter is important, as the hand-device interaction forces are always applied at a horizontal offset location from the device because hand and fingers are positioned to the side of the WFTS module.

B. Alignment Analysis

Misalignment between the physiological axes and the device axes can impact the accuracy of the recording. With the 10 mm adjustments steps of the slider, it is theoretically possible to keep the misalignment of both the wrist and finger axes at less than 2.5 mm. At the same time it should be said that the human wrist joint consists of multiple bones which do not rotate round a single axis and the four parallel MCP joints do not share a single axis. Therefore, it is likely that a larger misalignment will occur.

To assess the impact of these misalignments, a sensitivity analysis was conducted. The offset between the axes of rotation of the WFTS and the physiological axes was varied up to ± 10 mm. For each of these offsets, the distance between the point of application of forces by the wrist or finger segment (F_f and F_p) and the respective rotation axes was increased from 20 mm to 40 mm.

In Fig. 7 it is shown that increasing the offset between the axes of rotation increases the error, and placing the point of force application further from the rotation axes reduces it. A axes misalignment of 5 mm can introduce a error of approximately 20%. The error is mostly insensitive to changes in the point of application of the interaction forces. This indicates the need for precise alignment, but if this cannot be achieved the constant component of the error can be partially corrected for.

IV. Discussion

The Wrist/Finger Torque Sensing module (WFTS) measures the torque around the flexion/extension axes of the wrist joint and the combined metacarpal phalangeal (MCP) joints of

the fingers with a reasonable accuracy. The device is insensitive to torques around other axes. It can be used in combination with rehabilitation robots such as the ACT-3D, with isometric measurement stations, or as a stand-alone device. It is designed to investigate abnormal joint torque coupling at the paretic wrist and fingers following stroke by measuring isometric flexion/extension torques generated by the wrist and fingers during dynamic 3D movements of the paretic upper limb. Wrist and finger joint angles can be easily altered over the wide available range to examine the effects of changes in muscle lengths.

For the device to operate correctly, the human and device axes need to be closely aligned. This could be problematic, as the human wrist joint consists of multiple bones which do not necessarily rotate round a single axis. Similarly, there is no single axis for the four MCP joints in the fingers. Only some of the errors introduced by these misalignments can be adjusted for.

Another limitation is the lack of a thumb-torques measuring modules. The joint of the thumb is too small to use the same 1-DOF sensors as for the fingers and the wrist. Either a smaller sensor needs to be selected, or a more simple solution, as used in the WFFS module [16], can be added.

The addition of lightweight actuators could make the WTFS module suitable for simultaneous stiffness quantification during imposed wrist-finger movements.

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Fig. 1.
The Wrist and Finger Torque Sensor (WFTS) module. The module can be mounted to an isometric setup or a rehabilitation or diagnostic robot.

Fig. 2.

The uses of the WFTS module. Connected to the ACT-3D robot (top), to the robot for trials with young kids (bottom left), and to an isometric setup (bottom right). Note the mounting of the device such that the wrist and finger axes are aligned to the human axes. The black velcro straps fasten the hand tightly to the hand-palm and fingers interfaces of the WFTS module. When attached to the forearm-orthosis of the ACT-3D robot, the WFTS module records wrist and finger torques during 3D functional movements such as reaching in space.

Fig. 3.

Overview of the WFTS module. The module is placed next to the wrist and hand (see Fig. 2) with the wrist and finger axes aligned to the two axes of the module. The hand-palm and finger interfaces (not shown) are attached to the sides of the pale-red and pale-blue boxes respectively. Each box contains a 1-DOF tension-compression force sensor (white) mounted at a fixed distance from the axis. The finger and wrist flexion/extension angle can be set at discrete angles via bolted connections respectively between the dark-blue angle adjuster and the orange slider, and the dark-red angle adjuster and the black base. The distance between

the two axes can be changed in discrete steps via a bolted connection between the orange-slider and the light-red wrist box.

Fig. 4.

Expanded view of the WFTS module. The pale-blue finger box is freely hinged with ball bearings around the axis of the orange slider. The finger box is rotationally locked to slider via the white force sensor and the dark-blue finger-angle adjuster, with the adjuster fixed to the orange slider via a bolt. The pale-red wrist box is connected indirectly to the black base via the white force sensor and dark-red wrist-angle adjuster.

The free body diagrams (FBD) of the WFTS module. In blue, the finger and hand palm of the human limb. In orange, the schematic of the WFTS module. The setup is split up into four separate free bodies; two for the hand, two for the module. Given an exerted torque at the fingers (T_f) and at the wrist (T_w), the reasoning is as follows. The finger torque generates a finger-device interaction force F_f at an unknown distance L_{1f} from the joint axis. This causes a reaction force at the axis. These forces and torques are then transferred to the connecting bodies (black stripped lines) of the human hand palm and the finger component

of the device. Following this reasoning, the palm-device interaction force F_p is added to the bodies and the FBDs are balanced for forces and torques. As the device axes are aligned with the limb axes, the forces and torques in the device and in the limb are the exact opposite of each other. Therefore, the interaction force distance L_{1f} , L_{21} , L_{2f} do not need to be known (and can shift in time) to measure the finger T_f and wrist T_w torques. However, misalignment of the axes can influence the accuracy of the measurements (see Fig. 7).

Fig. 6.

Calibration plots for the WFTS module for the wrist (top figures) and finger (bottom figures) axes. Different calibration weights were placed at a fixed distance from the joint axes (left column). The measured voltage shows an almost perfectly linear relation with the torque load. To measure the effect of offset loading, a single calibration weight was placed at a fixed perpendicular distance from the axis at spaced horizontal offset distances from the center of the module. There is almost no influence of this offset on the measured voltage (right column).

Fig. 7.

Sensitivity of the torque measurement to axes misalignment and distance between rotation axis and point of application of the interaction force. The black solid line shows perfect alignment, where the measured torque is insensitive to the distance of the axis to the interaction force. The top and bottom stripped lines are for +5 and – 5 mm misalignments, respectively. The top and bottom dotted lines indicate +10 and –10 mm misalignments.