Development of a wrist manipulandum for assessment of motor control and biomechanics

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Abstract

The motivating principle behind this research is the development of a wrist manipulandum, which allows for the simultaneous dynamic control and measurement of wrist flexion/extension posture and angular velocity while measuring grip strength. Such a device is useful for gaining an improved understanding of motor control and biomechanics for patients following stroke when compared to healthy normal subjects. Object grasping and manipulation requires control of hand posture and also the force exerted on the object. Following stroke, there is impaired ability to simultaneously execute these two requirements. The manipulandum would be used in conjunction with an electromyography system to measure muscle activation while subjects are flexing and, or extending the wrist. This project supports research collaboration with Physical Therapy faculty with interest in stroke rehabilitation. In order to be useful in the development of a post-stroke physical therapy program the device must measure the grip strength of the subject while also measuring the angle of wrist flexion/extension at which the patient is acting.

Introduction

For grasping of objects in the hand, joint movements in the wrist and finger complex are primarily constrained by the length-tension relationships of the extrinsic and intrinsic multi-articular hand muscles that allow fine hand adjustments[1]. The grasping phase itself and the following phase of grasp release are automatically executed in a smooth and coordinated manner in healthy individuals, but are impaired in individuals with wrist and finger flexor spasticity and muscle weakness[2]. For example, following stroke, subjects have difficulty opening the hand for grasping, scaling the grip aperture according to the object size and properties, positioning of fingers on the object, activating muscles with sufficient force to eliciting grip forces needed to lift and hold the object, and lastly releasing the object after manipulation[3,4]. Most of these abnormalities are common to many neurological diseases and are caused by impaired co-activation of muscle agonists, muscle weakness (greater in extensors), and increased muscle tone. In rehabilitation, several manual techniques are frequently used to facilitate either the grasp or release phases. The techniques utilize the basic physiological mechanism inherent in the muscle tension-length relationship. For example, inability to activate finger flexors with sufficient force to lift an object is facilitated by passive extending the wrist and thereby increasing length and tension in the finger flexors. In contrast, grasp release is usually facilitated by flexing the wrist passively which in turn results in stretching of extensors and increasing their activities. The effect of using these manual techniques is variable, and depends to a large extent on the subjective evaluation of muscle properties by a therapist. In cases where the evaluation is incorrect, the grasp or release may be easily performed either without any active voluntary contraction, or instead be entirely unsuccessful.

Background

Robotically controlled manipulandum are used extensively for the investigation of the biomechanics and motor control of the human upper extremity. The manipulandum consists of one or more arms, or segments) which are attached to the human arm, or in some instances ending in a handle which is grasped in the hand. As such, the device serves to control and thereby alter the biomechanical or motor control environment and then subsequently measure the human response to the alteration. The manipulandum can then either be used in a kinematic study whereby data are collected from the manipulandum itself or also in a dynamic sense whereby additionally forces and moments generated by the human are measured in response to the altered environment. Many of the existing manipulandum have been designed to operate in two-dimensions because frequently, scientific questions can be sufficiently answered with experiments involving planar motion. These include existing two-dimensional manipulanda designed and used at Massachusetts Institute of Technology[5, 6] and Johns Hopkins University[7]. As mentioned, many experiments can be performed in two dimensions, however, manipulandum allowing three dimensional movements allow for experiments replicate the full nature of human motion. A more limited number of three dimensional manipulanda, often used in virtual reality environments have been described[8]. Although a few manipulandum can be procured from readily available sources, invariably most work involves utilization of custom designed and fabricated manipulandum which meet the specific needs of the research under exploration[9], and therefore are better posed to answer the specific scientific questions.

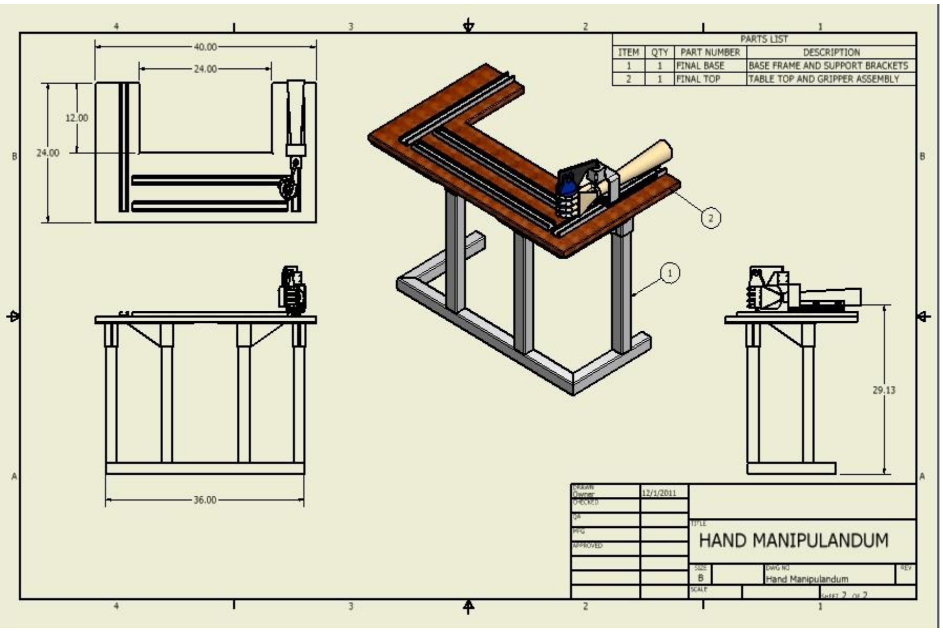
To address these drawbacks to using the very few readily available “off-the-shelf” manipulandum and to advance the manual techniques described above to the next technological level, a bimanual manipulandum was developed.

System/Manipulandum Design Evolution

A senior design team worked with a Physical Therapy faculty member to determine the most essential attributes of the manipulandum. The team conducted benchmarking and worked with the customer to decide on appropriate metrics and specificiations to describe performance of the manipulandum. After generating four conceptual designs, the team used a Quality Function Deployment (QFD) approach (Table I) of ranking the attributes against the metrics and specifications to arrive at the final design concept (Figure 1).

Table I: Customer needs for manipulandum as determined in design process (5-most important)

#	Customer Need	Importance
1	Statically measure grip of a hand at fixed angles of the wrist, relative to a pre-defined neutral axis	5
2	Measure the grip of a hand as grasp is applied over time	5
3	Fix the forearm to the manipulandum using restraint system	4
4	Measure the grip of the patient's thumb separately from the fingers	4
5	Record and display the output of sensors in an easy-to-read manner	5
6	Design manipulandum to test the left and right hand	4
7	Measure angle of the wrist at fixed positions	4
8	Rigidly fix manipulandum to increase accuracy of tests	3
9	Use office chair that manipulandum fastens to	1
10	User-friendly to operate and adjust	4
11	Construct apparatus for easy transportation	4
12	Design a device with the safety of all involved in mind	5



PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	FINAL BASE	BASE FRAME AND SUPPORT BRACKETS
2	1	FINAL TOP	TABLE TOP AND GRIPPER ASSEMBLY

Figure 1: Conceptual manipulandum design (in Catia).

Manipulandum Components

The manipulandum is attached to a custom fabricated table for secure mounting (Figure 2) and to allow repeatable, safe use in subject testing. The table allows for the manipulandum to be adjusted for use with testing of left and right extremities. Additionally, in order to match subject anthropometry, the table allows adjustment of the manipulandum relative to a standard office chair where a subject is seated for testing. A grip device, in the shape of a soda bottle, transferred subject grip from the fingers and thumb to load cells. Two different sized soda bottle grips, to accommodate subjects of varying anthropometry, were manufactured with a rapid prototyping machine.

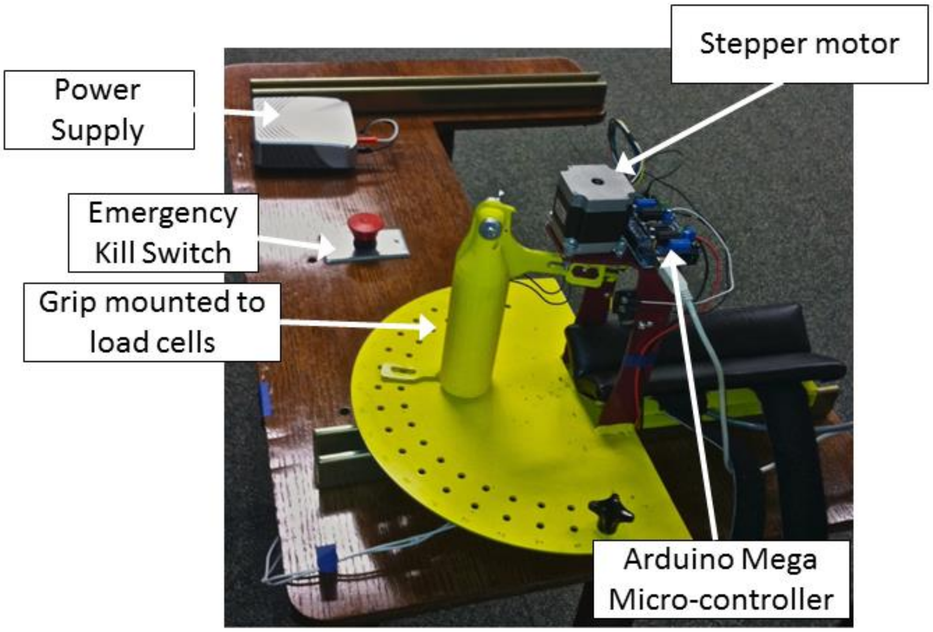


Figure 2: Manipulandum components.

To measure grip force of the fingers and thumb, two 445 Newton compression load cells (Measurement Specialties, Inc., FC-2331-0000-0100-L) were attached to a movable arm that rotated about the wrist flexion axis. The load cells utilize piezoresitive strain gages to convert force to voltage and have a linear relationship between force and voltage with sensitivity of 9 mV/N. Load cells were calibrated to ensure force measurement was accurate to within 0.1 N.

The movable arm was rotated about the wrist flexion/extension with an 8.0 kg-cm 6 Wire NEMA 23 stepper motor. The stepper motor was sized to move not only the grip device but also the subject's hand and wrist. Hard stops prevented excessive rotation of the arm in order to prevent the occurrence of exceeding a subject's maximum wrist flexion and extension.

An Arduino Mega microcontroller was used to control the stepper motor and to synchronize forces measured with load cells to rotation angle of the movable arm with subject's wrist attached. An Arduino R3 motor shield provided the interface for handling the stepper motor inductive load. Power for the Arduino Mega was supplied from the National Instruments SCB-68 and for the stepper motor from a standard power supply.

A custom LabVIEW Virtual Instrument (VI) was designed and implemented using the LabVIEW Interface for Arduino (LIFA) toolkit (Figure 3). The VI allowed for the tester to specify the maximum angles of wrist flexion and extension as controlled by the stepper motor. Additionally, the desired rotation speed of the movable arm attached to the stepper motor and wrist was set in the VI. The VI, along with the Arduino microcontroller, collected and synchronized the load cell data and wrist rotation angle before saving these data for *post hoc* analysis.

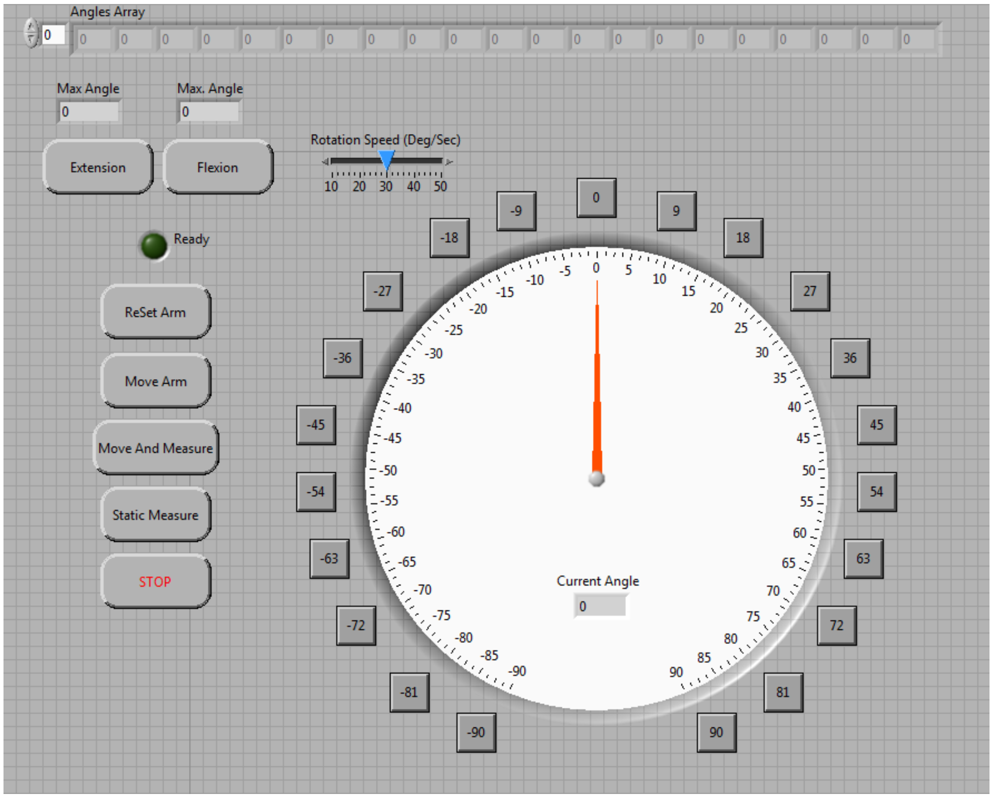


Figure 3: LabView Virtual Instrument (VI) front panel for control of manipulandum stepper motor and recording of force data from load cells.

Pilot testing and performance analysis

For testing, a health normal subject's forearm was secured to a supporting brace with straps and the subject was asked to grasp the grip device and the movable arm was adjusted in length to match anthropometry and to allow for smooth rotation of the wrist through the full range of flexion/extension (Figure 4). Following subject familiarization, pilot motions with the subject voluntarily flexing and extending the wrist were conducted to ensure grip strength data could successfully and safely be collected. Following the pilot motions, the stepper motor was used to control motion while the motion was controlled and data were collected using the LabView VI described earlier.

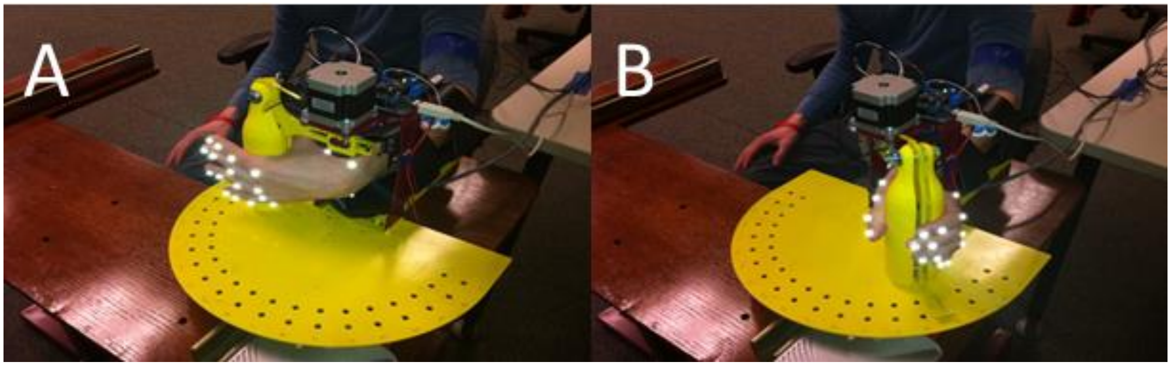


Figure 4: Manipulandum with subject's hand and wrist positioned in maximum (A) flexion, and (B) extension.

Results

Grip strength was successfully recorded when the wrist was in a static posture, when subjects actively varied the wrist flexion angle across the full range of motion and when wrist flexion angle was varied actively by the stepper motor (Figure 5).

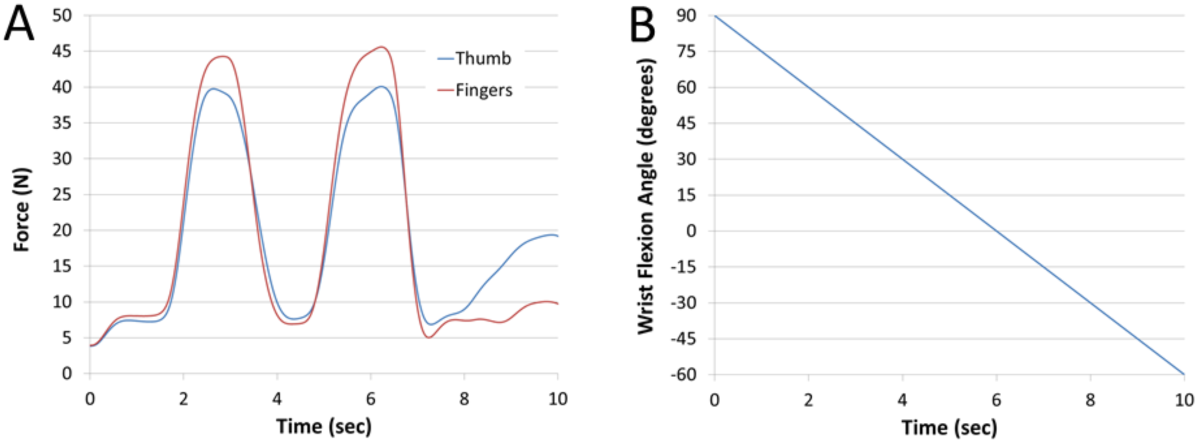


Figure 5: Data collected from manipulandum included (A) forces recorded with LabView from load cells while (B) wrist actively flexed by stepper motor.

Future Work

The device will be used to aid in understanding alterations in the muscle length-tension-activation relationship for subjects with and without pathologies causing impaired grip strength. With the data collected from the device, subject specific determination of the most optimal angular position of the hand for facilitation (not for substitution) of grasp and release in individuals with different severities of spasticity and muscle weakness after acquired brain injury (e.g. stroke, traumatic brain injury). During the initial pilot study, the activity of major finger/wrist flexor and extensor muscles and hand/forearm kinematic will be recorded for the system validation and confirmation that hand opening and closing took place. The pilot results will be used for refining the device that can be implemented later for re-training of the grasp and release functions in patient populations. The populations that can potentially benefit from the use of this device may include, but are not limited to patients with stroke, but can be used to understand motor control and biomechanics of patients with traumatic brain injury, spinal cord injury, Cerebral Palsy, and some orthopedic problems.

Relevance to Engineering Education

This project was performed initially as a senior design project and then further improved as a student research project with the goal of providing a working manipulandum suitable for recording measurements of grip strength for health normal subjects and patients with impaired motor control while the wrist flexion angle is passively or dynamically altered through the normal anatomical range of motion. The manipulandum will support the establishment of a collaborative line of research between engineers and physical therapists aimed at understanding motor control impairment in cases of Stroke, Parkinson’s disease and traumatic brain injury. Lastly, the device will be important in follow-on student projects for both engineering and as well neuroscience and physical therapy students and will be used in experiments to support improved understanding of motor control.

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