INTERACTION CONTROL FOR REHABILITATION ROBOTICS VIA A LOW-COST FORCE SENSING HANDLE

Andrew Erwin, Fabrizio Sergi, Vinay Chawda, Marcia K. O'Malley
Mechatronics and Haptic Interfaces Laboratory
Department of Mechanical Engineering and Materials Science
Rice University
Houston, Texas 77005
Email: ace7@rice.edu, fabs@rice.edu, vc9@rice.edu, omalleym@rice.edu

ABSTRACT

This paper investigates the possibility of implementing force-feedback controllers using measurement of interaction force obtained through force-sensing resistors (FSRs), to improve performance of human interacting robots. A custom sensorized handle was developed, with the capability of simultaneously measuring grip force and interaction force during robot-aided rehabilitation therapy. Experiments are performed in order to assess the suitability of FSRs to implement force-feedback interaction controllers. In the force-feedback control condition, the applied force for constant speed motion of a linear 1DOF haptic interface is reduced 6.1 times compared to the uncontrolled condition, thus demonstrating the possibility of improving transparency through force-feedback via FSRs.

1 INTRODUCTION

Each year in the United States 12,000 new cases of spinal cord injury (SCI) occur. Those who have suffered a SCI often experience complete or partial tetraplegia of the upper limbs, which can have a significant impact on a person's ability to perform the everyday activities required to live an independent lifestyle [1]. Rehabilitation robots, such as the RiceWrist [2], have shown success in rehabilitating the upper limb of SCI patients through intensive repetitive motion therapy [3]. This therapy consists of the patient either actively or passively moving a specific limb, such as the wrist, numerous times between two calibrated desired set points. Currently, the RiceWrist does not directly measure force at the end effector, but uses motor current as an estimate of force.

This approach can be implemented with success in transparent robots (i.e. direct drive robots with negligible dynamics), or through model-based dynamic compensation schemes for interaction control [4]. However, the accuracy of the computed estimate is often compromised by modeling inaccuracies, or neglecting higher order and nonlinear dynamical effects (i.e., friction). To overcome these limitations, force-feedback control schemes can be used to improve the accuracy of interaction control in non transparent manipulators. In force-feedback control, the force of interaction between the robot and the environment is measured and fed back to the controller driving the actuators, which specifies new desired force or position/velocity commands.

Our research group is interested in developing a means to measure interaction force at the end effector for the simultaneous measurement of interaction forces during therapy. Generally in robotic and haptic applications force is measured through the use of load cells [3, 5]; however, load cells are typically not well suited for a rehabilitation robot due to the form factor and cost [6, 7]. An alternative sensor to load cells are strain gauges [8], but using a strain gauge requires a compliant material which can also increase weight and complexity of the part. With the advent of thin film polymer force sensing resistors (FSRs), the ability to incorporate lightweight and small force sensors into a rehabilitation device is possible. Force sensing resistors have found applications in haptics and physiological studies. For example, by placing FSRs in a glove, the force from each finger and the palm of the hand can be recorded and used for richer sensing than that possible through load cells or strain gauges [6, 9, 10].

2 DEVELOPMENT OF THE RICEWRIST GRIP

Despite not directly rehabilitating grip strength, patients using the RiceWrist have demonstrated increased grip strength over

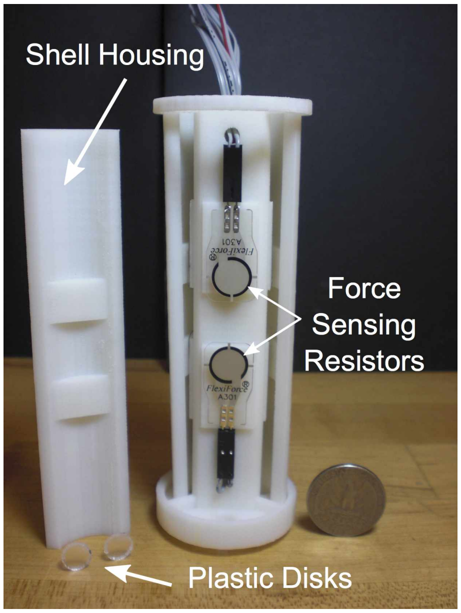

Figure 1. The RiceWrist Grip force sensing handle. The sensor measures grip force through six force sensing resistors (FSRs). Two flats on the shell housing contact plastic disks placed on the FSRs, transferring all the grip force to them for accurate measurement.

the course of therapy. Therefore, having the ability to monitor grip strength during therapy is of interest in our research efforts for upper limb rehabilitation robots. For this reason, the RiceWrist Grip has been developed by our lab, shown in Fig. 1, which can measure forces in three principal directions using six thin film force sensing resistors (FSRs). The RiceWrist Grip is incorporated into the RiceWrist-S [11], a serial version of the RiceWrist [2], to enable real-time monitoring of grip strength for the purposes of assessment and determination of rehabilitation efficacy.

To measure the axis of maximum grip force and directionality of interaction forces between the user and the handle during therapy, measuring force in at least three directions is necessary [12].The sensors are placed in two sets of three sensors, evenly spaced on the inner circumference of the handle. Three cylindrical shell slices, with two flats facing the sensors, are used so that all load is transferred to the FSRs. To control the load area on the FSRs, 1.5 mm thick and 8.5 mm diameter plastic cylinders were placed between the sensing area of the FSRs and the flats on the shells, increasing the repeatability of the FSRs response to an applied force (see Fig.1). Having two sensors per shell slice allows for the slices to deflect minimally, as opposed to having only one sensor, allowing for a stable grip. The main body of the sensor and the shell slices were created by a rapid prototyping machine with 0.51 mm resolution from Acrylonitrile Butadiene Styrene (ABS) plastic. The RiceWrist Grip weighs 92 g, is 34 mm in diameter, and 126 mm in length.

3 SENSOR SELECTION AND CALIBRATION

3.1 Force sensor selection

Tekscan's Flexiforce A301 force sensing resistor was chosen due to its size, 3% linearity, 2.5% repeatability, 4.5% hysteresis, 0-440 N force range, and 5 μs response time. The A301 sensor is 25.4 mm long and 0.203 mm thick with a 9.53 mm diameter sensing area. For this study, forces in the range of 0-15 N were desired so ATI Industrial Automation's Nano17 SI-12-0.12 six-axis force/torque transducer was used for calibrating the FSR. The sensor utilizes silicon strain gauges in order to provide six-axes of measurement, weighs 9.07 g, and is 17 mm diameter x 15 mm in height, with a range of 17 N in the z-direction and a resolution of 3.125 mN. The Net F/T box was used for signal conditioning of the Nano17 force sensor output.

When a force is applied to an FSR its resistance changes as $\frac{1}{R}$, and so its conductance, $C = \frac{1}{R}$, is mostly linear with the applied force (Fig. 2). In order to provide a linear voltage reading, an inverting op-amp circuit was designed. With this configuration, the output voltage is given by

$$V = -V_{in}\frac{R_f}{R_{FSR}} \tag{1}$$

where V is the FSR output voltage, V_{in} the input voltage to the FSR, R_f a feedback resistor, and R_{FSR} is the variable resistance from the FSR. The feedback resistor and input voltage to the FSR need to be chosen appropriately to allow for the output voltage to remain within the op-amp supply voltage range for every admissible value of applied force. For this study, R_f was chosen to be 100 kΩ and V_{in} was chosen to be -6.6 V. Calibration of the FSR was performed by placing a plastic disk between the FSR

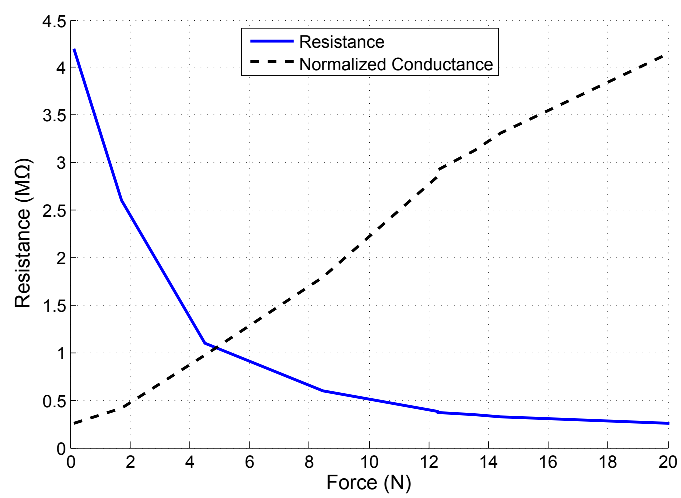

Figure 2. Experimentally measured resistance vs. force curve for the FSR. The conductance of the sensor is linear to applied force so utilizing an inverting op-amp allows for a linear relation between output voltage and applied force.

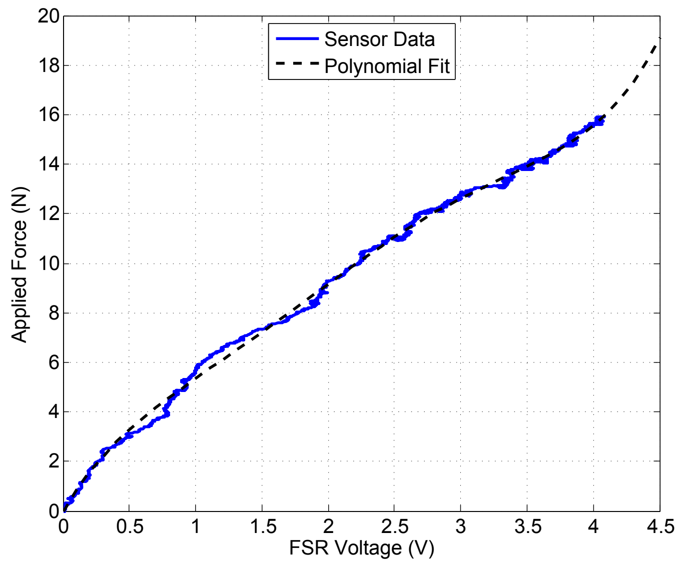

Figure 3. Calibration of the FSR voltage with force measured with the ATI Nano17 force transducer. The calibration resulted in a fifth order polynomial fitting of the data to account for the nonlinearity of the sensor at low forces.

and Nano17 force sensor to allow for all load to be transferred to the FSRs sensing area. At no load, R_{FSR} is greater than 5MΩ which allows for zero voltage to be measured at zero force.

3.2 FSR calibration

The reading from the FSR sensor was calibrated with the force measured with the ATI force sensor, by manually applying increasing levels of force in the compression direction. The resulting calibration can be seen in Fig. 3. The calibration curve in Fig. 3 shows a slightly non-linear response of FSR voltage to applied force. The sensor has a higher sensitivity in the low-force region and then settles on a lower (but mostly constant) sensitivity value after this break-in region. A fifth order polynomial fitting was applied to interpolate the data, as already proposed by [13]. In our case, the fifth order polynomial was chosen as

$$F_a = 0.09V^5 - 0.98V^4 + 3.75V^3 - 6.57V^2 + 9.06V - 0.01 \quad (2)$$

where F_a is the force applied to the FSR. The polynomial allows for interpolation of force values throughout both the non-linear and linear range of the sensor. From this calibration, the FSR can now measure forces between 0-15 N accurately. This accuracy was examined by measuring forces from the ATI Nano17 force transducer and the Flexiforce A301 sensor and comparing the two (Fig. 4). The comparison shows that the maximum difference between the two measurements is 1.45 N, a difference of about 10%. Depending on the application this accuracy of the FSR could be acceptable and its accuracy will be evaluated in this study.

4 FORCE-FEEDBACK CONTROL

A 1DOF testbed was used in order to evaluate the use of FSRs as a force measurement device for implementation of interaction controllers. An ABS housing was mounted to an aluminum platform which was translated on linear bearings. The platform was connected to a brushed DC motor (RE40, Maxon Motors Corp.) that controlled the motion of the platform through a cable transmission (see Fig. 5). In this setup, direct force-feedback controllers can be applied by measuring the force at the port of interaction between the actuated device and the subject.

A proportional-integral (PI) force controller was developed as shown in Fig. 6, acting on the force estimated from the FSR using (2). By setting a value of desired force $F_{des} = 0$, the robot is trying to render a transparent haptic interface to the user, such that a very small force is required in order to move the device.

In these conditions, a subject applied forces to the handle to regulate the motion of the slider, imposing a movement of 25 mm in around 1 s at a relatively constant speed. During this experiment, the motor was either powered off, or current-controlled as in the scheme shown in Fig. 6, using the VoltPaq Q8 from Quanser Inc and a Matlab-Simulink model sampled at 1 kHz, translated in Real-Time code with a Quanser USB Q8 board for data acquisition. The two experimental conditions allow comparison of the effort required to complete the task. It is worth noticing that in the mentioned conditions, the main source of non-linearity in the transfer of force between the actuator and the subject is provided by the static friction in the linear bearings.

It can be seen in Fig. 7 that friction compensation was

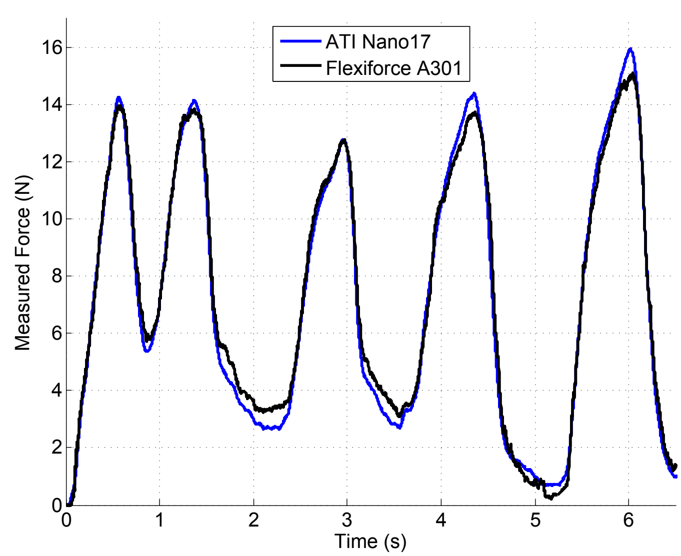

Figure 4. Comparison between the force measured with the FSR and with ATI Nano17 force/torque sensor, in a dynamic compression test.

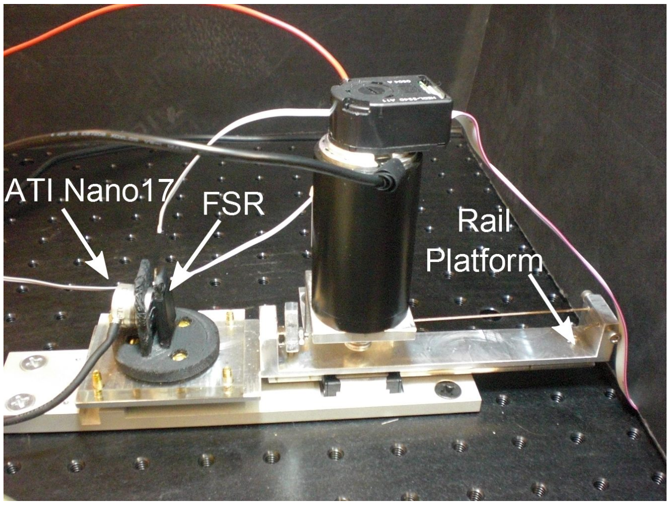

Figure 5. The FSR is attached to an ABS housing attached to an aluminum slider, which slides on a linear bearing, driven by a DC-motor actuated cable transmission. The ABS housing also serves as an alignment of the center of the ATI Nano17 and FSR allowing for forces to be transmitted from the user to the load cell, to the FSR, and finally to the platform.

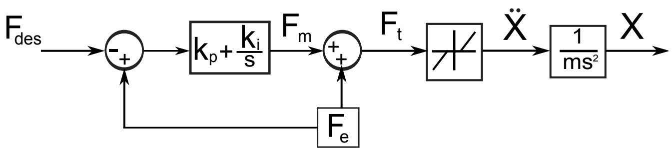

Figure 6. Block diagram representation of the zero-force control experiment. In the figure, F_{des} is the desired force (0 for this experiment), F_e is the external force applied by the user, k_p is the proportional gain and k_i is the integral gain applied on the error signal to the motor, and F_m is the motor force. The external and motor force are both applied to the system and if larger than static friction result in motion of the system. When the user force is non-zero, an error signal is sent to the motor in order to achieve transparent behavior.

successfully obtained with the simple force-feedback scheme shown in Fig. 6, thus validating the use of the FSR as a sensor suitable for implementation of interaction controllers in human-interacting robots. To quantify the improvements in interface transparency, the mean force required by the user was calculated for representative tasks of the two conditions, such as those shown in Fig. 7. Using the forces measured from the ATI Nano17, the mean force applied for the no control case was 1.71 N and 0.28 N for the controlled case. Thus, with the interaction controller 6.1 times less work was required to move the system, compared to having no controller. From this result, although FSRs may not measure force as accurately as commercial force sensors, they could still be useful for measuring interaction forces and for serving as a sensor for force-feedback controllers.

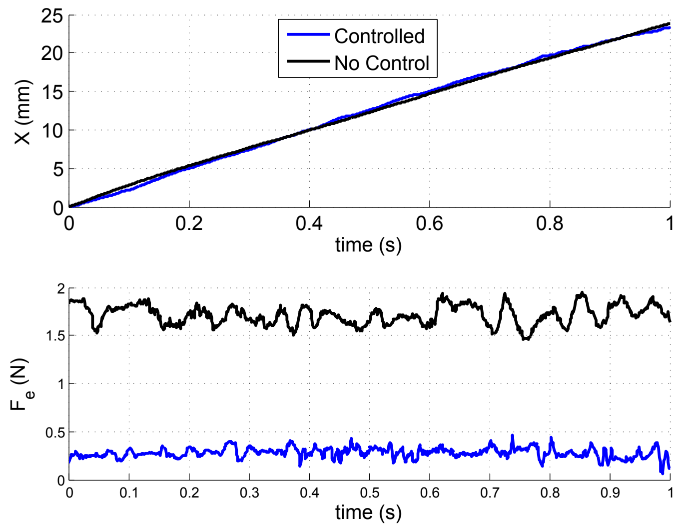

Figure 7. (top) Applied position during the interaction test, during the considered experimental conditions. (bottom) Interaction force measured in the two experimental conditions. The average force required for the same motion in the controlled condition is approximately 6.1 times lower.

5 CONCLUSION AND FUTURE WORK

The RiceWrist Grip force sensor has been developed using six force sensing resistors to measure grip forces. Preliminary testing showed that the force sensing resistors used on the RiceWrist Grip could be successfully used to regulate interaction using force-feedback controllers. This study has further examined the ability of force sensing resistors as a force sensor to reduce friction felt by the user when interacting with a robot. It was found that user effort was decreased by 6.1 times when moving a 1DOF rail-platform, by imposing a simple proportional-integral force feedback controller, with a null desired force. Additionally, in the 0-15 N range error in force measurement of the FSR can be kept to 1.5 N allowing for accurate force measurement. In the future, use of a more sophisticated controller along with exploring the use of the controller on the RiceWrist-S platform [11] will be investigated.

ACKNOWLEDGMENT

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