

Design of active feedback for rehabilitation device

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Abstract. Sensor systems are an essential part of automated equipment. They are even more important in machines that come in contact with people, because they have a significant impact on safety. This paper describes the design of active feedback for rehabilitation device driven by pneumatic artificial muscles. Here are presented three methods for measuring the load of the robot. The first is a system composed of Force Sensitive Resistors (FSR) placed in the handle of the device. Two other methods are intended to measure the load of the actuator composed of artificial muscles. The principle of one method is to measure the difference in filling pressures of the muscles, second is based on strain measurement in the drive cables. The paper describes advantages and disadvantages of using each of these methods in a rehabilitation device

1 Introduction

Musculoskeletal rehabilitation is an essential part of the healing process of patients who have experienced a traumatic injury or stroke limiting their range of motion. But rehabilitation exercises carried out by a physiotherapist are time-consuming and expensive. For these reasons, there is an endeavor to at least partially automate this task with usage of robotic rehabilitation devices. Their advantage is that the patient himself can choose the time and intensity of the exercise and especially in the case of simpler devices it is also possible to use them at the patient's home.



Figure 1. Rehabilitation device driven by pneumatic artificial muscles

In our department we are developing device for rehabilitation of the upper limb joints. It is designed for exercising shoulder and elbow joint at the same time. It's in the form of exoskeleton, so its kinematics reproduces kinematics of the human arm. The main specific of this device is actuator used to drive him - pneumatic artificial muscles.



Figure 2. Rehabilitation device driven by pneumatic artificial muscles - rear view

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Device as is shown in Figure 1 and 2 can perform passive rehabilitation exercises. For these exercises, it is sufficient that the device have a control loops for position and speed control of the device joints. But at some stage of recovery, it is necessary to start with active exercises in which the patient has to use his own strength. For the automated rehabilitation system, this means that this force should be measured and regulated. However, force measurement is problematic part in the design of sensor system. Since this device is specific by its purpose (rehabilitation) and also because of its drive (pneumatic muscles), there are no ready-made solutions that can be directly applicable. Because measured values should be used for direct control, this method must provide them in real time, without significant delay and without so called time errors.

2 Analysis of force measurement

Principled model of robotic arm with one joint driven by a pair of antagonistically connected artificial muscles is shown in Figure 3. On this model there are shows possible placements of force measuring system. In this case, the load is considered to be solely on the end of the robots arm.

The load can be measured on these three places:

1. at the point of contact,
2. at the robots arm - measurement of deformation,
3. in the actuator - measurement of load.

2.1 Measuring deformation of the robots arm

In this method, the force is measured indirectly as a deformation of the robots arm. For small deformation measurement in experimental mechanics but also in practical applications there are used strain gauges and load cells. For measuring the load of rehabilitation robot we considered two methods. The first is application of strain gauges directly to the robots arm. But this includes one difficult task. It is necessary to create the point, in which the deformation will be sufficient for measurement with satisfying resolution, while maintaining the strength of this element. This disadvantage can be eliminated by usage of bending load cell. These sensors mostly consist of a steel body on which the strain gauges connected to Wheatstone bridge are mounted. They are designed to measure strain in their nominal range but they can withstand some overload (typically 150-200%) [1]. Sensor like this can be embedded in the robots arm. The disadvantage of this solution is its dimensions and weight. Because of the material of load cell (mostly steel), the sensor placed on the end of kinematic chain can create significant torque.

2.2 Measurement of actuator's load

Rehabilitation device is designed so that each member of the kinematic chain has one degree of freedom. This is where the actuator operates and also where we need to measure load. In conventional robots that use electric

actuators, the load is mostly determined indirectly by measuring the current that passes through the motor. When using a pneumatic actuator this solution can't be used. But in the devices driven by artificial muscles other variables specific to this type of drive can be measured. Application of external forces to such an actuator leads both to change of pressure in both pneumatic muscles and also to change of stress in other components such as cables, chain, pulleys, etc.

3 Methods selected for further evaluation

For further consideration, we have selected three measurement methods. We choose these methods based on their advantages but also for their affordability and suitability for incorporation into existing rehabilitation device.

3.1 Force Sensitive Resistors (FSR)

FSR are passive electronic components that change their resistance according to applied force. These sensors consist of several thin layers of polymer so that application of force to the active area results in reduction of electrical resistance. Mechanically and also by range of measurement are these sensors designed to measure force of human touch. FSRs are not intended to accurate measurements like strain gauges.

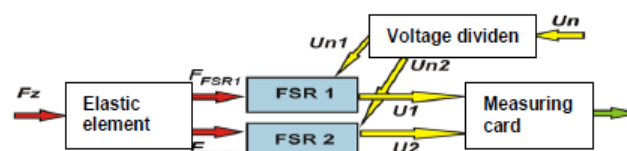
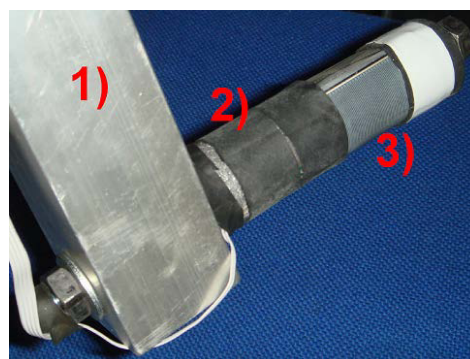


Figure 3. FSR sensors mounted on handle – 1) robots arm, 2) handle, 3) FSR

The force between rehabilitation device and patient is transferred mainly through the handle. This is place where direct contact occurs on relatively small area, which can be covered by conventional sizes of these sensors (0.25 to 25 cm²). Output characteristic of the sensor (resistance dependence on the strength) is roughly linear, so simple algorithms are sufficient for the signal

processing. Because this is a simple passive element, this characteristic can be modified by various electrical connections. If necessary, it is also possible to create different types of output - voltage, current, frequency and so [2]. To determine the force in the direction of one axis, it is necessary to know the values measured in opposing sensors (F_{x1}, F_{x2}).

The force on this axis is then the difference of their values ΔF_x :

$$\Delta F_x = F_{x1} - F_{x2} \quad (1)$$

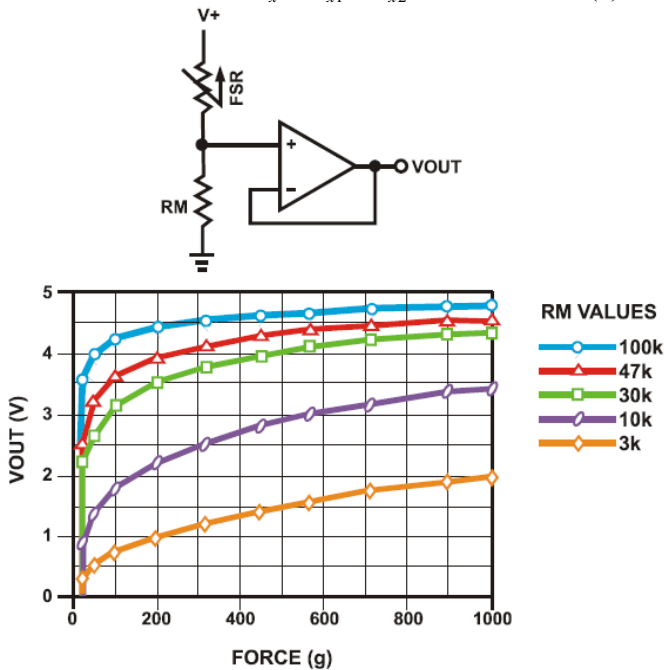


Figure 4. Connection of FSR to voltage divider (up) and its output characteristics (down) [2]

Key parameters, which determine if these sensors will be used in rehabilitation device, are accuracy and repeatability they can achieve. Accuracy, as stated by one of the manufacturers of these sensors [2], is generally between ± 5 to $\pm 25\%$. This value depends on the particular measuring system, on the way as the force is applied and also on the quality of the sensor. Significant increase in accuracy can be achieved by calibrating the sensors mounted directly in the system, in which it will be used. The second important parameter is the repeatability. This largely depends on variations in location and distribution of the load. The more consistent the load is the better results can be obtained with repeated measurements. But in rehabilitation we are not able to provide the same grip of the handle even when exercising same patient. This problem gets even worse if the same machine has to serve multiple users. We can reduce these impacts by constructing appropriate handle with proper placement of sensors. The use of thin layers of flexible material, which overlays the active area of the sensors, can more or less (depending on the thickness of the layer) distribute the load. Another option is to use auto calibration system before each exercise, which would eliminate differences between patients.

3.2 Measuring actuator's load based on pneumatic pressure

When the force is applied to the muscle, it changes its length. With the change of length it also changes its volume, which in a closed system leads to a change in pressure. This means that we can determine load of the robot by measuring values of pneumatic pressure in muscles. The process of calculating force from pressure is described bellow. First, we must determine value of the nominal difference between the pressures in the muscles ΔP_n at given position (measured by encoder). For this purpose it is necessary to assemble the model or mathematical dependence of pressure on the angle of the joint φ .

$$\Delta P_n = f(\varphi) \quad (2)$$

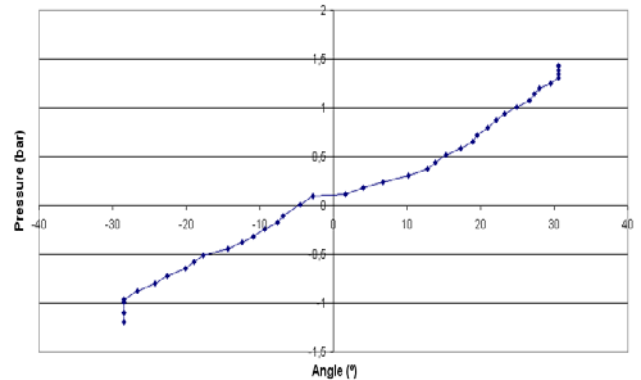


Figure 5. Dependence of pressure difference on angle of the joint

A complication in this step can be a various non-linear properties, which are characteristic for these actuators. However, it has significant impact on accuracy of this method of measurement. The next step is to calculate the actual pressure difference between values ΔP_s of pressure in these muscles (P_1, P_2).

$$\Delta P_s = P_1 - P_2 \quad (3)$$

Finally we can calculate the torque (M) as the function of difference between real and nominal pressure differences. Because the ratio of transmission is known and constant, we can then calculate the force.

$$M = f(\Delta P_s - \Delta P_n) \quad (4)$$

Different types of sensors can be used for pressure measurement. It is possible to use differential sensor, which provide directly the difference between two pneumatic pressures. But here, the more useful solution is to use single ended sensor for each muscle so it can be used also for different tasks (like in algorithm, which prevents complete exhaust of muscle). The disadvantage of this measuring method is that the measured values can be affected by pressure fluctuations caused by pneumatic valves during operation. This phenomenon is less significant when we use control methods that change the pressure in muscles smoothly (proportional valves, etc.). Another optimization can be done by mounting sensor in proper location. Since the pressure fluctuations are largest near the valve, pressure sensor should be connected as close to the muscle as possible (Fig. 6 left). However,

best location is on the other side of the muscle, opposite to the opening where the valve is connected (Fig. 6 right). But for this, it is necessary to use muscle that is opened on booth sides.

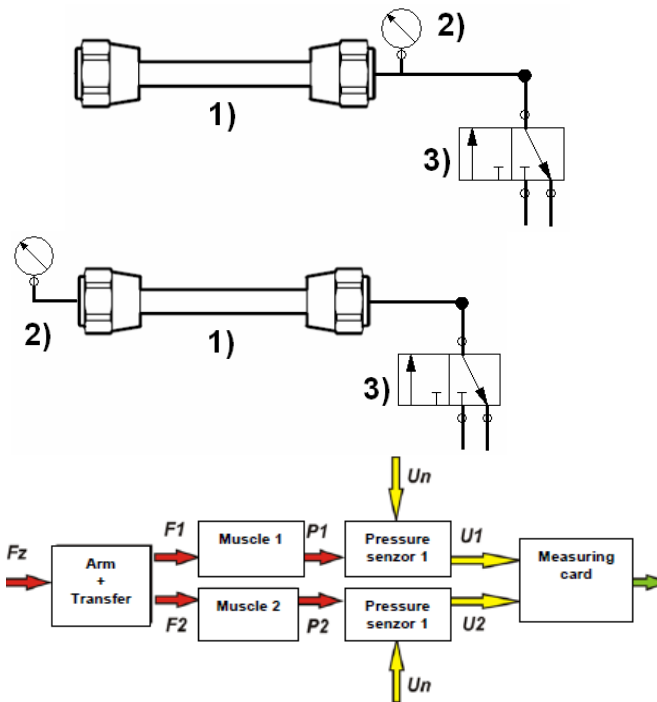


Figure 6. Options for placement of pressure sensor on muscle opened on one (up) and booth ends (down)

3.3 Measuring actuator's load based on strain in cables

Strain in the cables can be measured by load cells. Sensors for measuring tensile forces are small in size and relatively light and thus can be easily incorporated into the system. On Fig. 7 it is possible to see an example of their placement between pneumatic muscle and cable. Dimensions of this sensor are $\varnothing 34 \times 18 \text{ mm}$, so it does not increase the outline of a muscle in diameter and only slightly increases its length. Since booth muscle and cable transfer force only in one axis, sensor can be loaded only by tensile stress. Although the sensor is placed on the moving component, the movement of the muscle is in the order of centimeter, so the supply and signal conductors don't limit its use. Also measurement apparatus can be placed relatively close to the sensors. Processing of measured values is similar to the previous case. For the determination of the force it is necessary to calculate the difference ΔF between forces in each cable (F_1, F_2).

$$\Delta F = F_1 - F_2 \quad (5)$$

Even if the forces measured on unloaded arm should be theoretically balanced, in the practical implementation it is necessary to consider the effect of gravity. This affects the robots arm differently depending on its position and

also on the position of other members of the kinematic chain.

Therefore, as in the previous case, it is necessary to determine a dependence of the force (F_G) on the position of the arm (φ).

$$F_G = f(\varphi) \quad (6)$$

Then the effect of this force is subtracted from the measured values to get the real value of force exerted by the patient (F_p).

$$F_p = \Delta F - F_G \quad (7)$$

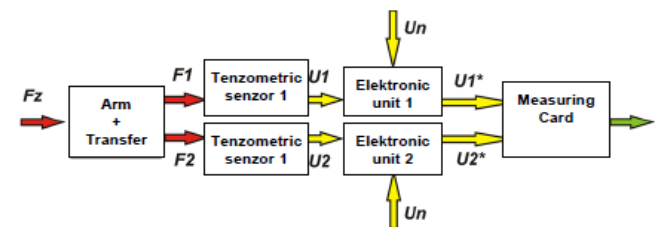


Figure 7. Load cell for measuring tensile forces – 1) muscle, 2) load cell, 3) cable

4 Conclusion

Force feedback is essential for the automated device that is intended for active rehabilitation. But in the device driven by pneumatic artificial muscles, we can not use the force measuring system used in conventional robots. It is therefore necessary to assemble a measuring system which takes into account his specific characteristics and requirements. Analysis of the available options shows that load can be measured in three locations: at the point of contact, at the robot's arm or in the drive. For closer comparison we selected three methods. The first is measurement in the handle of the device using FSR sensors. Other two methods use the fact that the force applied to the robot arm creates appropriate response in the drive. In case of actuator composed of pneumatic muscles, this load can be determined from the change in filling pressure in each muscle. Because the pressure sensors are a standard part of systems containing pneumatic circuits, such measurement requires no additional hardware components. Application of the load also results in the strain in mechanical parts of the drive and can be measured by load cells. Although this method is relatively complex, it gives results least influenced by other processes and random errors. These three methods will be evaluated in our department to determine the most

suitable method for measuring force in unconventional rehabilitation device.

Acknowledgement

The research work is supported by the Project of the Structural Funds of the EU, Operational Programme Research and Development, Measure 2.2 Transfer of knowledge and technology from research and development into practice. Title of the project: „Research and development of intelligent nonconventional actuators based on artificial muscles”, ITMS code: 26220220103, by the Slovak Grant Agency VEGA contract Nb. 1/0911/14 "Implementation of wireless technologies into the design of new products and services to protect human health" and by the Ministry of Education, Youth and Sports of the Czech Republic within the National Sustainability Programme project No. LO1303 (MSMT-7778/2014) and also by the European Regional Development Fund under the project CEBIA-Tech No. CZ.1.05/2.1.00/03.0089

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