

# A Low-Cost Haptic System for Wrist Rehabilitation

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## Abstract

*While the regular treatment for wrist stiffness is physical therapy or surgery, researchers are looking for an alternative, more efficient and automatic procedure by means of robotic applications. In this paper, we propose a low-cost system exploiting a haptic interface aided by a glove sensorized on the wrist allowing the identification of the wrist orientation; in this way, by using virtual reality, the patient is able to make some motions that are very essential for his/her rehabilitation process and, by exploiting the wrist orientation tracking, he/she can be trained and guided to reach different goals of increasing complexity.*

## 1. Introduction

After trauma or surgery, decreased wrist range of motion, flexion and/or extension, abduction/adduction or pronation/supination can be a challenging problem [1,15]. In fact, physical therapy, orthoses, and additional surgical interventions may not restore the desired functionality even after an intensive rehabilitation program (Figure 1). For that reason, haptic interfaces have become an important part of virtual reality simulators for rehabilitation and training.

On the other hand, the widespread use of these systems is still limited by the high costs of special purpose haptic interfaces. However, the high number of units produced in gaming hardware offers a promising low-cost alternative for specialized high quality/high cost haptic interfaces.

Therapists actually spend a considerable amount of practice time in differential diagnosis of these losses and in selecting appropriate intervention strategies to restore passive and active motion according to the pathology and to prevent loss of range of motion after injury [7, 11, 16]. More specif-

ically, previous research has already shown that the haptic interface *Novint Falcon* is a suitable platform for robotic application and can be used to build inexpensive multiple DoF (Degrees of Freedom) interfaces.

Thus, starting from the low cost haptic interface *Novint Falcon* [8], we built a new haptic system for wrist rehabilitation combining the haptic interface with a glove able to catch the orientation of the patient's wrist. In our case study, the patient wears this glove and uses it with the haptic interface, thus moving his/her wrist in a virtual environment created to allow a good motion for the wrist rehabilitation. In this way, we are able to detect the orientation of the patient's wrist in real time, when the patient is using this rehabilitation system. This would allow both patients and therapists to discover the patients' current capabilities, thus helping patients to reach the different targets proposed for their rehabilitation.

The paper is organized as follows: Section 2 provides an overview of related work in the field of wrist rehabilitation, followed by a brief introduction of our approach to address this problem. Section 3 describes the haptic interface that we analyzed to design our new device: a detailed analysis of the motor characterization, kinematics and criticality of this haptic device is also carried out. Section 4 discusses the increase to the Grip of the Haptic Interface used, while Section 5 presents the new system for wrist rehabilitation that we have designed and developed. Finally, some preliminary experimental results are shown in Section 6 and conclusions with possible future work are provided in Section 7.

## 2. Related Work

Several systems for wrist rehabilitation have been developed in research centers and universities, for example IMT3, MIME, RiceWrist, HWARD, the Okayama Univer-

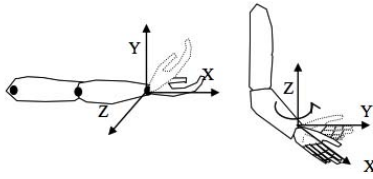


Figure 1: Wrist motion

sity pneumatic manipulator [4, 9, 14]. The majority of them is also used for rehabilitation in health centers and hospitals, often coupled with MIT-MANUS, ARMIN, MIME, HapticMaster and wire-based devices for rehabilitation of proximal limb [9].

Robot assisted therapy is primarily based on goal-directed point-to-point movement involving multiple DoFs; its main purpose is to increase the RoM (Range of Motion) of the paretic limb in order to regain motor abilities for the activities of daily living. On the contrary, the regular physical therapy of wrist rehabilitation consists in a splinting treatment for each single DoF at time; there have been many studies looking at the splints' effectiveness and what type of splint would be best.

Static progressive splinting is a time-honored concept: for more than 20 years, clinicians have recognized the effectiveness of static progressive splints to improve passive range of motion. Splint designers then sought a way to improve the technique with components that offer infinitely adjustable joint torque control and are also easy to apply, lightweight, low-profile, and reasonably priced. Dynamic splints use some additional component (springs, wires, rubber bands) to mobilize contracted joints. These dynamic-pull functions aim at providing a controlled gentle force to the soft tissue over long periods of time, which encourages tissue remodeling without tearing.

The issues that make the dynamic or static progressive splinting technically difficult include determining how much force to use, how to apply the force, how long to apply the force, and how to prevent additional injuries to the area. Things could change if the dynamic splinting is delivered using devices which are able to modulate torque delivering and space the range of motion.

Therefore, we intended to approach the robotic therapy for wrist rehabilitation using a new device providing both us and the patients some information about the progress of their work during a virtual game that we have specifically designed for helping them during their rehabilitation process. However, differently from other systems for wrist re-



Figure 2: Novint Falcon

habilitation, such as [13], which is based on an exoskeleton structure supporting and blocking the limb, ours consists of a sensorized glove and a haptic interface, thus allowing the patient to be more free to perform some natural movements.

### 3. The Novint Haptic Interface

We decided to use Falcon, an inexpensive 3-DoF haptic device made by Novint for the gaming industry. The controller uses a form similar to the one of the delta-robot configuration and, by means of this form, it builds an apparatus interesting for research on control and estimation problems for robots involving parallel linkages.

This paper describes a work conducted at the University of Naples Federico II in characterizing the Falcon's grip by exploiting a new glove that we designed for improving the rehabilitation process of the patients with wrist problems.

The Novint Falcon (Figure 2) uses a translational only, 3-DoF variant of the delta-robot configuration. The Falcon's design also incorporates a removable end-effector that can be replaced with different grips, for example a pistol-like grip designed for use in first-person shooter games, or other custom attachments, such as a pen-holder or gripper. This device is currently applied in robotics and haptics outside of the gaming industry, arguably for its accessibility.

For most links of the Falcon, full triaxial analysis is not required due to the planar motion of the components; for example, the main leg links connecting to the base can only rotate around a single pivot (and the second mass moment of inertia is sufficiently characterized by a single term in one plane), and the end effector is constrained to translational motions only.

### 3.1. Motor Characterization

The Novint Falcon is actuated by three Mabuchi RS-555PH-15280 motors whose motion can be monitored by a coaxial 4-state encoder with 320 lines per revolution. These motors are directly coupled to a 14.25 mm diameter drum, upon which a 0.5 mm diameter cable is wrapped. The cable runs around the outer edge of the main leg links at a radius of 56.0 mm, and is tensioned by a spring at the inner end of the leg. This arrangement allows for a very low friction and robust actuation mechanism effectively providing a 7.62:1 (outer leg radius to drum radius, plus correction for cable width) gain to the motor output about the main leg's pivot without resorting to the use of gears.

### 3.2. Kinematics

The position of the end effector is described by the triple  $(x, y, z)$ , with the  $x$ -direction defined as horizontal and the  $z$ -direction perpendicular to the base. Each leg has an equal angular spacing of  $2\pi/3$  around the  $z$ -axis, with the top-most leg having an offset of  $-\pi/12$  radians ( $15^\circ$ ) measured from the vertical. In the home position (encoder values of zero), the angle from the base-leg joint to the leg-shin joint (angle of a line to the  $z$ -axis) is approximately  $50^\circ$ .

### 3.3. Criticality of the System

The most common criticality of the delta-robot form is its limited workspace.

The three limbs of the Falcon work in kinematics (and with an appropriate control methodology, dynamics) in order to actuate the end-effector, but each leg is limited by the reach of the connected linkages. This appears in a workspace bounded by warped tri-hemispherical regions overlapping along the common longitudinal  $z$ -axis.

The most attractive feature of the Falcon for research purposes besides its form and availability, is the transparency of the control interface. We have direct access to a variable that we have shown can be easily translated to motor forces. This is as opposed to many commercial (non-research) robotic platforms whereby the internal firmware provides manufacturer developed control loops with only a velocity or position demand interface available to the user.

In minimally invasive surgery (MIS), virtual reality (VR) training systems have become a promising education tool. However, the adoption of these systems in research and clinical settings is still limited by the high costs of dedicated haptic hardware for MIS [3, 12].

In this paper, we present ongoing research towards an open-source, low-cost haptic interface for wrist rehabilitation. We demonstrate the basic mechanical design of the device, the sensor setup as well as its software integration.

Thus, we describe a low-cost system exploiting a haptic interface aided by a glove sensorized on the wrist allowing to identify the wrist orientation; moreover, by using VR, the patient is able to make some motions that are very essential for his/her rehabilitation and, by exploiting the wrist orientation tracking, he/she can be trained and guided to reach different goals of increasing complexity.

## 4. Increasing the Haptic Interface's Grip

As previously mentioned, we designed a glove where we added a specific hardware on the top of the wrist.

Through this glove, we are able to get information about the wrist orientation during the movement of the hand within a given task assigned to the patient (Figure 3).

More specifically, to measure the inertial parameters, we used a system that incorporates three sensors - an ITG-3200 (MEMS triple-axis gyro), ADXL345 (triple-axis accelerometer), and HMC5883L (triple-axis magnetometer) - to form an Inertial Measurement Unit (IMU) of 9 DoFs. The outputs of all sensors are processed by an on-board microcontroller ATmega328 and sent over a serial interface; thus, this enables the 9-DoF IMU to be used as a very powerful control mechanism [5]. Moreover, since it is programmed through the open source Arduino Software, this IMU outputs its roll, pitch, and yaw data, characterizing the orientation of the wrist, via serial. We used the Arduino IDE to program our code onto the 9DOF, connecting to the serial TX and RX pins with a 3.3V FTDI breakout and selecting the Arduino Pro Mini (3.3v, 8mhz) as our board. Since our 9 DoFs operates at 3.3VDC, we used LiPo batteries as an excellent power supply choice. Furthermore, a bluetooth module has been used to establish a bidirectional communication channel enabling the wireless interaction between two endpoints.

## 5. The System for Wrist Rehabilitation

The design of the haptic interface is heavily based on the Novint Falcon gaming hardware, inertial sensors, virtual reality environment and open-source software [6]. As the workspace of the Novint Falcon is too small for certain interventions, software-based scaling of the instruments' movements is used to allow adaption to a broad range of applications. In this way, an inexpensive system for wrist rehabilitation based on a low-cost but very powerful haptic interface has been designed and developed; more in details, the haptic interface has been improved by means of a glove sensorized on the wrist able to detect information about the wrist orientation when the patient is completing specific tasks of his/her rehabilitation path in a virtual environment specifically designed for guiding patients to per-



Figure 3: The New Grip

form six specific motions that are very essential for the wrist rehabilitation [2, 10].

Thus, the patient will be seated at a computer and wear the glove on the injured hand. Then, he/she will hold the haptic interface with the same hand and try to move his/her hand and consequently his/her wrist according to the received instructions about the task to complete in a virtual environment specifically designed: the better is his/her performance, the more difficult the following task will become. In this way, by monitoring in real time the wrist orientation, the patient can realize his/her progress within his/her rehabilitation process and is highly motivated to complete his/her tasks as soon as possible.

## 6. Motion Rehabilitation Preliminary Experimental Results

This section presents the preliminary experiments conducted on our device for wrist rehabilitation.

Ten naive stroke outpatients with no previous exposure to robot therapy have received 6 weeks of training on our wrist device. They have performed some specific exercises of increasing complexity aimed at allowing them to gradually move and thus rehabilitate the wrist. For instance, several tasks dealt with placing some virtual space objects into a container by going through a path specifically built for allowing patients to move their wrists in several angles.

Thus, the improvements in their hand functions have been observed: the obtained results can be considered promising, as the ten patients achieved on average a 40% reduction of virtual game errors after 2 weeks, 55% after 4 weeks and 70% after 6 weeks (Figure 4). However, all the

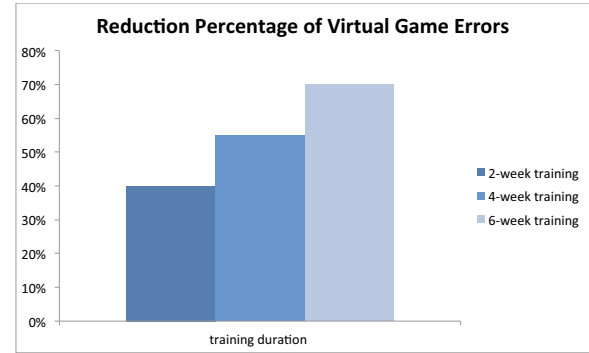


Figure 4: Reduction percentage of rehabilitation game errors

ten subjects improved the ability of their injured hand by means of our device.

After completing the rehabilitation process, the patients filled out a questionnaire to report their impressions about the haptic system used. Each subject was asked to answer 3 questions (How useful, How educational, How real time) using a 5-point Likert scale. As we can see in Figure 5, subjects expressed positive opinions about their experiences with the system; this preliminary result can be considered very promising for future work.

## 7. Conclusion and Future Work

This paper describes a low-cost haptic system for wrist rehabilitation. More in details, this system exploits a haptic interface aided by a glove sensorized on the wrist for the identification of the wrist orientation, which allows patients to be trained and guided to reach different goals of increasing complexity during their rehabilitation process in a virtual reality. Some preliminary experiments about our device usefulness have been conducted and seem to be very promising.

Future work will be devoted to significantly extend our experiments, by involving a higher number of patients with different kinds of wrist injuries in trying our device, in order to obtain a more significant feedback. Moreover, we are planning to conduct a comparison between patients using the device and patients not using it, in order to discover if there is any statistically significant difference between the two groups in terms of recovery time.

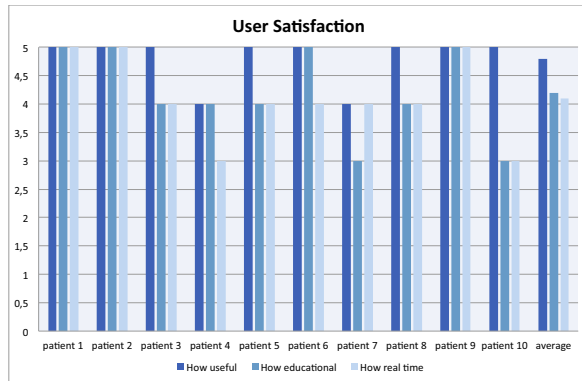


Figure 5: User Satisfaction

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