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An Experimental Setup to Evaluate Sensory Substitution Methods for Upper Limb Robotic Prostheses

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Abstract

Sensory substitution is an easy, cost effective and mostly-preferred method to provide artificial sensory feedback to users of robotic prostheses. This sensory feedback, such as artificial proprioception, is provided through different sensory modalities, such as vibration, at different locations on the body. In this study, we propose a new methodology and an experimental setup, which are to be used to determine contribution of artificial proprioception feedback on coordinated manipulations. The setup consists of a novel haptic interface, an input device, a force sensor, and a virtual environment. Experiments were performed to technically evaluate the developed haptic interface. To further validate the interface, we conducted a psychophysical test in which subjects compared real and virtual springs with different stiffness constants. Results showed that the setup was able to successfully render the intended springs. The experimental methodology is based on the Strength-Dexterity test, which works on the principle of buckling of compression springs. Since this unstable task highly depends on coordination of force and position, its virtual implementation provides a novel platform to test sensory substitution techniques.

Keywords: Sensory substitution, Haptic feedback, Robotic prostheses, Virtual environment

Üst Ekstremite Robot Protezleri için Duyusal İkame Yöntemlerinin Değerlendirilmesi Amaçlı Bir Deney Düzeneği

Öz

Duyusal ikame, robotik protez kullanıcılarına yapay duyu geribildirimi sağlamak için kullanılan kolay, uygun maliyetli ve çoğunlukla tercih edilen bir yöntemdir. Böyle bir duyusal geribildirim, mesela yapay propriosepsiyon, titreşim gibi farklı bir duyusal kiple vücudun farklı yerlerinde sağlanmaktadır. Bu çalışmada, yapay propriyosepsiyon geribildiriminin koordineli manipülasyonlar üzerindeki katkısını belirlemek için kullanılabilecek yeni bir yöntem ve deney düzeneği önerilmektedir. Düzenek yeni bir haptik arayüz, bir girdi cihazı, bir kuvvet algılayıcısı ve bir sanal ortamdan oluşmaktadır. Geliştirilen haptik arayüzü, deneylerle teknik olarak değerlendirilmiştir. Ayrıca, deneklerin gerçek ve sanal yayları karşılaştırdığı bir psikofizik test de yapılmıştır. Sonuçlar, deney düzeneğinin amaçlanan yayları başarılı bir şekilde sunabildiğini göstermiştir. Önerilen deneysel yöntem, yayların bükülme prensibiyle çalışan Dirençlilik-Maharet testine dayanmaktadır. Bu kararsız görev büyük ölçüde kuvvet ve konum

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koordinasyonuna bağlı olduğu için, bu çalışmada önerilen sanal uygulama tabanlı deneysel metod, duyusal ikame yöntemlerini test etmek için yenilikçi bir ortam sağlamaktadır.

Anahtar Kelimeler: Duyusal ikame, Kuvvet geribildirimi, Robotik protezler, Sanal ortam

1. INTRODUCTION

There has been a significant effort to provide sensory feedback to persons with an amputation since they lack these information [1]. Modality matched feedback is a vital element for conveyance of physiologically relevant touch feedback [2]. Here lies the most critical setback of commercially available prostheses. In Dudkiewicz et al. [3], it is reported that rejection rate in body powered and electric powered prostheses were %29 and % 30, respectively. The main reasons for prosthesis rejection were dissatisfaction with function and lack of realistic sensory information [4].

Proprioception provides central nervous system with information about the spatial location of body parts. It has been proved that proprioception plays a key role in body coordination during movements where more than one joint moves [5]. Despite the benefits of proprioceptive feedback, only few studies have provided this feedback [6–11]. In these studies, proprioceptive information was provided through another sensory modality at another location. Although this kind of "sensory substitution" is an easy and cost effective way to provide feedback, users have not performed any better in prosthesis control than with visual feedback alone [12,13].

Our aim in this study is to developed a new experimental setup and a novel methodology to be used to understand the effect of sensory substitution of proprioception (*artificial proprioception*) on upper limp prosthesis control. In literature, there is already comprehensive information about the importance of sense of touch on prosthesis control focusing on pressure feedback. Proprioception, on the other hand, has been studied only in few studies [13-18]. In these studies, the role of proprioception on perception of limb position was investigated while isolating position and force control tasks in single degree-of-freedom (DOF) manipulations. However, coordinated manipulation of unstable objects requires feedback control. Therefore, our objective in this study is to develop a method to identify contribution of artificial proprioception on a manipulation task in an unstable, 2-DOF virtual environment. For this purpose, we have designed and developed a new experimental setup and a methodology.

In the following sections, first the literature review is given. Then, the experimental setup is presented. On subsequent sections, physical and psychophysical evaluation of the setup are discussed. Finally, the planned experiments for evaluating sensory substitution methods for upper limb robotic prostheses are discussed.

2. LITERATURE REVIEW

Only a few experiments have been conducted with able-bodied subjects, investigating different aspects of human hand and finger force exertion capabilities. One of the most comprehensive studies was performed by Cuevas et al. in a series of experiments [19-21]. A challenging task which can demonstrate human sensorimotor ability to adjust finger motion and force is dynamic precision pinch [19]. In literature, studies on myoelectric prosthesis model such robotic systems in a virtual environment to mimic prosthesis usage. Then, a computer input device is used to interact with this model in the virtual environment. For instance, Gurari et al. [22] developed a 1-DOF haptic interface in which they intended to compare the benefits of visual and proprioceptive feedback. Subjects tried to perform a targeted motion task. Improving their experimental design Blank et al. [13] revised the former experiment in which different sensory information were delivered in different trials in contrast to their first design where proprioception and force feedback were delivered simultaneously. Their purpose was to simulate a real spring. Their results indicate that performance was elevated with proprioceptive feedback under non sighted condition and some sighted conditions as well.

In the studies mentioned above [13–18, 22], the role of proprioception was investigated while isolating positioning and force control tasks and focused on single-DOF manipulations. Therefore, in this study, a method focusing on a finger manipulation task in an unstable, 2-DOF virtual environment is proposed. Since this unstable task highly depends on coordination of force and position, this virtual implementation provides a novel platform to test sensory substitution methods.

3. METHODOLOGY

The proposed methodology is based on an unstable task called "Strength-Dexterity Test" [19–21], utilizing buckling of compression springs. In this test, subjects are asked to compress a spring up to buckling. We have implemented a virtual model of this test.

3.1. Experimental Setup

The experimental setup consists of a novel 2-DOF haptic interface, a 2-DOF input device, a 6-DOF force sensor, two vibration feedback motors, and a virtual environment (Figure 1). The haptic device and the input device have been designed to interface with the index finger. Their workspace and output capabilities have been specified based on the human finger capabilities. While the input device has isotonic input capability, the force sensor (ATI Nano 17) is used as an isometric input device. The haptic interface is used to provide position/force feedback.

Figure 1. Experimental setup consists of a 2-DOF haptic interface, a 2-DOF input device, a 6-DOF force sensor, two vibration motors, and a virtual environment

The haptic interface is composed of a parallel mechanism, two DC motors with quadrature encoders (Maxon DCX22L and ENX 16 EASY) and a thimble (Figure 2, left). Rotations of the motors are transmitted to translation and rotation of the thimble through a series of joints, belts, gears and linear rails. The encoders have a resolution which corresponds to translational resolution of 0.068 mm and rotational resolution of 0.16°. The motors are driven by two motor controllers (Pololu 18V7) for smooth operation. All high-level control commands are programmed in two Arduino Mega 2560 boards. Friction compensation algorithms are used so that users can have a transparent interaction with the virtual environment. Haptic loops are updated at a rate of 1 kHz.

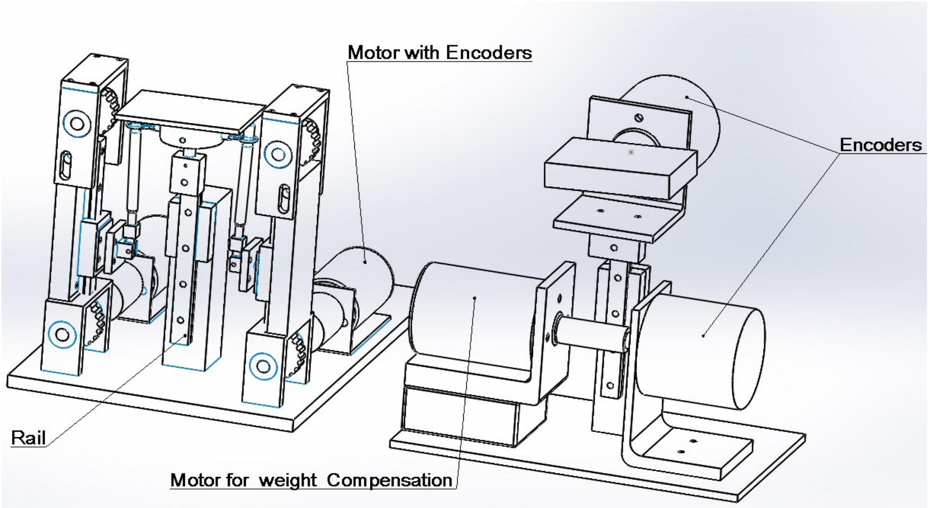

Figure 2. Hardware schematics: (left) haptic interface, (right) input device

The input device is comprised of two encoders (OMRON E6B2), a brushed DC motor (Mitsumi Motor RS-540SH) and a thimble (Figure 2, right). This 2-DOF device is kinematically analogous to the haptic interface. The encoders are used to measure finger displacement. A pinion-and-rack mechanism guided on a linear rail is used to convert translation into rotation for measurement purposes. Weight and friction of the device are compensated with the motor operating at a constant current.

Vibration feedback was delivered to subjects using four 12 mm vibration motors (Precision Microdrives Ltd.). Two of them was mounted on top of each other as suggested by Cipriani et al. [23]. Vibration amplitude was modified by selectively activating the vibration motors.

We have developed the virtual spring model in the Simulation Open Framework Architecture (SOFA) platform, which is an Open GL-based graphical program developed in C++. The spring is modeled as a deformable object composed of mechanical meshes. Mechanical properties of the virtual spring are selected in a way to resemble a real spring behavior. The virtual spring is free to move in 2 DOF and its both ends are constrained by virtual planes to replicate boundary conditions of the real spring. The virtual environment loop is updated at 60 Hz.

3.2. Physical Evaluation

We implemented the common evaluation practices available in the literature to validate our setup [24].

3.2.1. Friction Compensation

For friction and gravity compensation, we measured the resistive forces while moving the end effector manually across the workspace of the haptic device with a constant speed. A force sensor (ATI Nano 17) was used for the measurement. We assumed that friction force was constant across the rail when moving in one direction. Hence we allocated a constant amount of force for compensation of gravity and friction force based on the direction of movement. The motors are driven with a certain input to apply these direction-dependent compensation forces to the haptic interface. After the gravity and friction compensation, the reaction forces were measured again.

3.2.2. Force Output Capability

One of the primary specifications of a haptic device is maximum force output capability. In order to measure force output capability of the haptic device the force sensor (ATI Nano 17) was attached between the tip of the device and a stationary rigid constraint. Output forces were measured while the motors were commanded with a slowly increasing and decreasing ramp input. Motors were driven up to their specified nominal torque. We also obtained the nominal force of motors when supplied with sufficient amount of current by utilizing motor data sheet which maps resultant motor force to current supplied to the motor. As motors were fixed and did not rotate, corresponding currents represent the stall torques and we can be sure that motors apply the amount of force indicated in the data sheet. We loaded and unloaded motors in two conditions: 1) without compensating for the device self-weight and friction of the rails, and 2) with implementation of a friction compensation strategy.

3.2.3. Virtual Spring Simulation

To validate whether our setup is able to render virtual springs in a transparent manner, we simulated a series of springs with certain stiffness and measured the output force while the virtual spring was pressed via the haptic device.

3.3. Psychophysical Evaluation

We conducted a psychophysical test to evaluate the perceptual characteristics of the setup. In this test participants were asked to distinguish the difference between real and virtual springs. The purpose of this study was to evaluate how precise subjects can distinguish stiffness between virtual and real springs and determine baseline parameters for further application of our setup. The Institutional Review Board of Bogazici University has approved the experimental protocol.

3.3.1. Subjects

Seven volunteers (2 women and 5 men) aged between 22 and 28 participated in the experiment. One subject was left-handed and six were right-handed. All subjects were able-bodied persons who did not suffer from any motor skill difficulty. None of the subjects was familiar with any kind of haptic interface.

3.3.2. Procedure

Each subject was briefed about the experimental procedure and trained how to interact with the system. Ethical consent was taken from each volunteer before the beginning of the experiment. Before we start the experiment, subjects were given five samples of real springs to work with so that they could gain an insight about stiffness range of the springs used in the experiment. Our experimental design consisted of two tasks; pushing real springs through the input device and virtual springs through the haptic interface. Subjects were looking at the virtual spring model on the screen on both cases. Subjects' vision was occluded by covering the entire setup with a piece of fabric so they did not see which device they are interacting with. Thus, they did not have any visual cue about whether they were touching a real or a virtual spring. They had to bring their dominant hand under the fabric and experimenter guided their index finger inside the thimble which was mounted on the end effector as shown in Figure 1. Subjects were instructed not to start the trial until the experimenter gave them permission to do so. Subjects were asked to compare two springs and state verbally whether they felt different or not. If subjects indicated that the springs felt different, they were asked to choose the stiffer spring by saying “left” or “right”. Their answers were recorded in the experiment form. Subjects were allowed to retry each spring as many times as they wished. Five different springs were used in the experiment. Their stiffnesses were at least 22% different from each other in order to have perceptually different springs [25]. Each real spring was compared with the virtual implementation of the other four springs. The whole experiment was repeated three times for each subject which lead to a total number of 60 trials. Virtual and real spring combination sequence was randomized using a MATLAB code so subjects would not become biased or learn the sequence of incoming trials. Overall the experiment lasted approximately 45 minutes for one subject. A two-minute-break was given to subjects in the middle of the experiment in order to prevent finger fatigue.

4. RESULTS

4.1. Physical Evaluation Results

The results of the friction compensation experiments are shown in Figure 3. As shown in this figure (orange curve), the reaction forces in upward movement and downward movement converge to a certain amount, except for the distal areas of the rail. Therefore, our assumption that friction force was constant across the rail when moving in one direction is plausible. After the gravity and friction compensation, the reaction forces were measured again. The results are presented as blue lines in Figure 3. As seen in the figure, the resisting force is considerably less when gravity and friction compensation is applied. In this case the resisting force does not exceed 1N throughout the workspace.

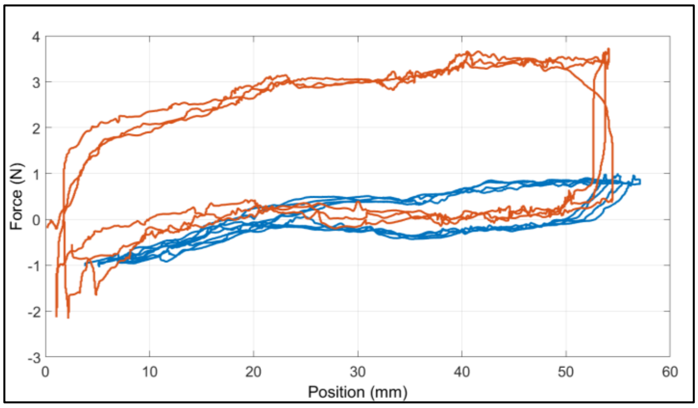

Figure 3. Resistive forces without compensation (Orange) and with friction compensation (Blue)

The results of the force output capability measurements showed that there was a noticeable hysteresis between loading and unloading which was due to existence of friction in the rail however the hysteresis decreases obviously when friction compensation was added to the actuation loop, which can be seen in Figure 4. It is also worth to mention that non linearity of the system decreases as friction is compensated however, hysteresis of the setup still is a noticeable value.

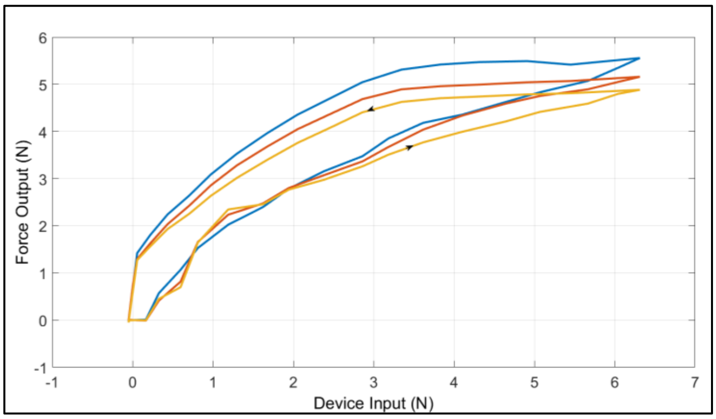

Figure 4. Device input versus force output with friction compensation. Blue, red and orange lines represent the first, second and third trials, respectively

An example from the virtual spring simulation test is shown in Figure 5. Spring force versus position is plotted for a virtual spring having a stiffness of K = 760 N/m. Five different springs were simulated. Their stiffness values and the measured values are tabulated in Table 1. This procedure was repeated 5 times for each spring. Data presented in Table 1 shows that the rendered stiffnesses closely match the intended values. Hence we can claim that our haptic device can be regarded as a reliable instance of a spring rendering system.

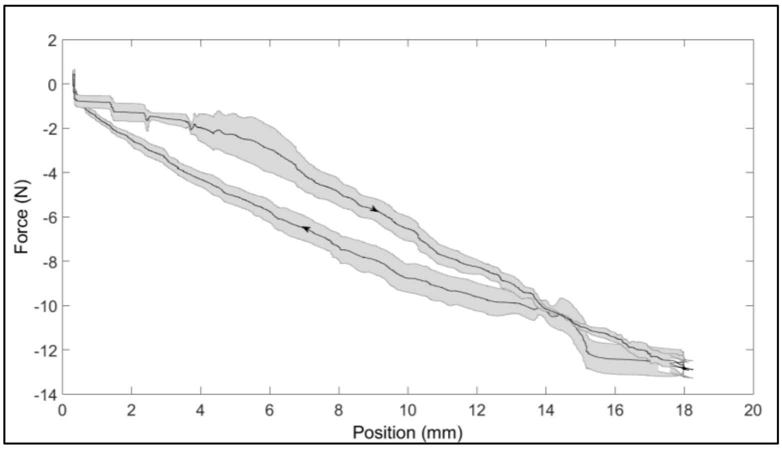

Figure 5. Virtual spring simulation. Solid line and shaded area represent the mean and the standard deviation of the five measurements, respectively. Arrow indicates the direction of movement

Table 1. Intended and measured spring stiffness

	Spring Constant (N/m)	
Spring #	Intended	Measured
1	260.0	256.1
2	760.0	768.1
3	1280.0	1208.2
4	2100.0	2014.7
5	3000.0	2940.1

4.2. Psychophysical Evaluation Results

Responses obtained from subjects were analyzed in terms of correct discrimination of spring stiffness. The mean correct answers among the subjects were 72.9%. As we had chosen the springs in a way to have stiffness differences higher than the just-noticeable difference of stiffness, which is conservatively 22% [15], we would expect 100% correct answer for fully-transparent haptic rendering. An average of 72.9% which is well above the level of chance, indicates that the virtual springs rendered by the haptic device closely follow the intended spring behavior.

5. DISCUSSION

The experimental results showed that the subjects were able to correctly discriminate springs even if they were virtual which demonstrates effectiveness of our setup. Intrinsic perceptual differences between the haptic device and the input device made subjects consider the haptic device to be stiffer than the other one. Another reason which lead to this perception is the fact that because of active feedback, such as friction compensation in the haptic interface and some ripples in its movement, subjects mistakenly interpreted the virtual spring stiffer (they misinterpret mechanical actuation as stiffer). This drawback is inevitable in haptic devices due to mechanical and electrical characteristics of a mechatronic system. Usage of higher precision components might diminish this obstacle. Another reason which made the virtual spring be felt stiffer is the asymmetries in the rails and over constraints in the system. These over constraints were unavoidable in designing the parallel kinematic structure of the mechanism.

6. FUTURE WORK: THE VIRTUAL STRENGTH-DEXTERITY TEST

As mentioned in the introduction, the developed setup will be employed in a future psychophysical study aiming at determination of contribution of artificial proprioception on a finger manipulation. In this future study, subjects will be asked to compress the virtual spring up to buckling. They will interact with the virtual spring with the index finger of their dominant hand through the haptic interface, the input device and the force sensor. Input condition will be either isotonic (when the input device is used) or isometric (when the force sensor is used). Three feedback conditions will be tested: visual only, wrong-modality sensory substitution of proprioception (artificial proprioception through vibration) and modality-matched sensory substitution of proprioception (position and force feedback). Subjects will get position/force feedback on their contralateral index finger through the haptic interface. Vibration feedback will be applied using the small coin-type vibration motors. Seven experiments will be performed under different input and feedback conditions. First three experiments will define the base lines for the best and worst performances. Protocol for each experiment is as follows:

1. Subject compresses the virtual spring and receives the force and position feedback through the haptic interface.
2. Subject compresses the virtual spring through the input device. No force feedback is provided.
3. Subject compresses the virtual spring through the force sensor. No position feedback is provided.
4. Subject compresses the virtual spring through the input device. Vibration feedback proportional to spring force is provided on the contralateral index finger.
5. Subject compresses the virtual spring through the force sensor. Vibration feedback proportional to spring position is provided on the contralateral index finger.
6. Subject compresses the virtual spring through the input device. Force feedback is provided on the contralateral index finger through the haptic interface.
7. Subject compresses the virtual spring through the force sensor. Position feedback is provided on the contralateral index finger through the haptic interface.

6. CONCLUSION

In this study, we have proposed an experimental methodology in order to quantify contribution of sensory substitution of proprioception on multi-DOF tasks. For this purpose, we have developed an experimental setup in which subjects are asked to compress a virtual spring up to buckling. Our approach differs significantly from the previous studies, such as [13,14,17], in terms of the employed task which involves a dynamic manipulation in an unstable environment. Since this unstable task highly depends on coordination of force and position, the method provides a novel platform to study sensory substitution. The proposed setup and methodology have contributions to the literature in many terms such as the nature of the task, higher degree of freedom, elevated task difficulty, and a new haptic device.

7. ACKNOWLEDGEMENTS

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