# A Novel Haptic Glove (ExoTen-Glove) Based on Twisted String Actuation (TSA) System for Virtual Reality

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**Abstract.** A compact and light-weight wearable haptic glove (ExoTen-Glove) based on Twisted String Actuation (TSA) system is presented in this paper. The proposed system uses two actuators with small size DC motors and an integrated force sensor based on optoelectronic components. ExoTen-Glove can provide force feedback to the thumb on one side, and to the other fingers grouped together on the other side. This configuration has been selected to provide the user force feedback during the execution of grasping tasks by means of a virtual reality environment to feel the stiffness of different objects. Thus for the first evaluation of the ExoTen-Glove, we only focus on the feedback from thumb and index finger. The paper reports the design of the haptic glove, the description of the actuation system, the embedded controller, and the preliminary experimental evaluation of the device. The ExoTen-Glove has been evaluated by means of a simple experiment in virtual environment with 2-DOF grasping activities of rigid and compliant virtual object (spring) using thumb and index finger to show the applicability of the system for rehabilitation and haptic feedback purposes. Results of the experiments showed that the haptic ExoTen-Glove improved stiffness evaluation significantly for the high and low spring stiffness and users were able to distinguish virtual spring stiffness differences easily with high accuracy.

**Keywords:** Force feedback · Twisted String Actuation system Wearable · Virtual reality · Stiffness discrimination Tendon transmission system

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## 1 Introduction

Over the past years various robotic systems conceived to be directly interfaced with the human hand have been developed, mainly utilized as haptic interfaces for telemanipulation [1,2], or for medical training [3,4], and for interaction with nano and micro scale phenomenon [5,6]. A five-fingered Haptic interface consists of a 6-DOF arm and a 15-DOF hand has been implemented in [7,8] that allow the user to interact with the virtual object without imposing any weight and providing 3D fingertip force display.

One of the main functionality of the robotic hands is haptic interfaces that are conceived to drive teleoperated systems, both virtual and real, therefore the main purpose is to follow the user movements, minimizing or controlling the interface dynamics during free motion, and providing proper feedback to the user in case of contact with virtual or real objects on the teleoperated system. Haptic interfaces can provide various feedback, such has force [9,10], pressure feedback [11,12] or vibro-tactile [13,14]. Wearable haptic devices with the force feedback not only allow the user to grasp and feel the virtual objects in a natural way during interaction with the environment but also allow the user to manipulate virtual objects in a more natural way. The CyberGrasp ™ [15] is a grounded force feedback system which can provide an individual force (up to 12 N) roughly perpendicular to the fingertip of each finger that can be combined with a separately available CyberGlove ® dataglove that provides joint angle information of the hand and fingers. The Rutgers Master II-ND glove [16] is a haptic interface designed for dextrous interactions with virtual environments that provides up to 16 N force feedback to each finger using pneumatic actuators. Most of the wearable haptic gloves have substantial number of actuators and hence they are bulk and heavy. If the haptic gloves are made lighter, smaller, easier to wear and cheaper via a new actuation method, such as twisted string actuation (TSA) system, they would become common human-machine interaction interfaces for the interaction in virtual reality.

The robotic system design requirements present many common aspects, such as the adaptability to different users, the mobility of the device that should not interfere the user's movements and the capability of controlling the feedback provided to the user. In this paper, the development of a haptic ExoTen-Glove driven by twisted string actuation (TSA) system [17–19] is reported. The TSA system allow the implementation of low-cost, light-weight and powerful tendon-based driving systems, based on small DC motors characterized by low torque, high speed and very limited inertia that makes it suitable to be used in highly integrated mechatronic devices, e.g. robotic hands and exoskeletons. Also, the slender structure of TSA system makes it particularly suitable to be used in wearable robotic devices. The TSA system has been used in different applications such as DEXMART hand [20] and a 6-DOF cable-driven haptic interface [21].

The proposed ExoTen-Glove is able to provide the user a force feedback during the execution of grasping tasks in a virtual reality environment. The design of the haptic gloves is oriented to the maximum simplicity, therefore it is implemented as a wearable system without any external bulky mechanism to guide the finger movements and support the actuation used to provide the force feedback, but relying on the skeleton structure of the hand itself as supporting mechanism for the tendon-based actuation system.

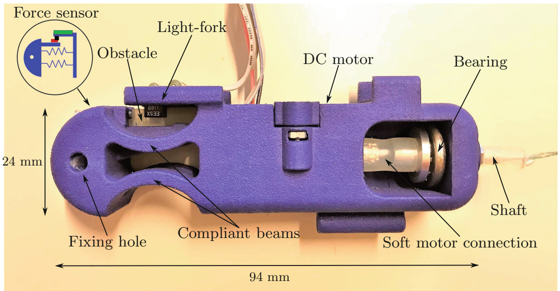


**Fig. 1.** Detailed view of the TSA module prototype.

The paper is organized as follow. In Sect. 2 the overall device is described, focusing on the design, the actuation system and the controller. Section 3 reports the testing environment and the experimental activity carried out to evaluated the device functionality. In the final Sect. 4 the outcomes of the works are summarized and comments on future work are given.

## 2 System Description

### 2.1 Actuation Design

The TSA module design and its integrated force sensor has been described in details in [22–24] and therefore here only a brief summary of its main features is reported. The TSA module structure (see Fig. 1) is made of Polyamide (PA 12) manufactured by Laser Sintering (SLS) and it is composed of:

(i) a frame hosting the DC motor (maxon DCX) and the encoder (maxon ENX), sensor electronic components, with a dimension of (94 mm length, 24 mm height, 19 mm width),
(ii) a fixing hole to connect the module to the supporting frame;
(iii) a force sensor based on optoelectronic component (Omron EE-SX1108) to measure the load applied to the string;
(iv) a pair of axial-symmetric compliant beams that function as a linear spring granting a certain compliance to the structure as well as the implementation of the force sensor;
(v) a shaft supported by an axial bearing at the point of the twisted string connection to both reduce the friction and prevent the transmission force from damaging the motor;

(vi) and a silicon tube for coupling the motor and transmission shafts to provide ample flexibility in order to solve problems due to misalignment of the rotational axes of the motor and the transmission shaft;
(vii) the string (Dyneema with a diameter of 0.16 mm) itself connects the motor module with the linear moving element.

This particular structure allows the transmission force to be completely supported by the output shaft through a combined bearing while the motor is only used to transmit the necessary torque for driving the twisted string actuation to the output shaft. The weight of an ExoTen-Glove actuator, including force sensor, DC motor, encoder and mechanical component like shaft and bearing is 40 g.

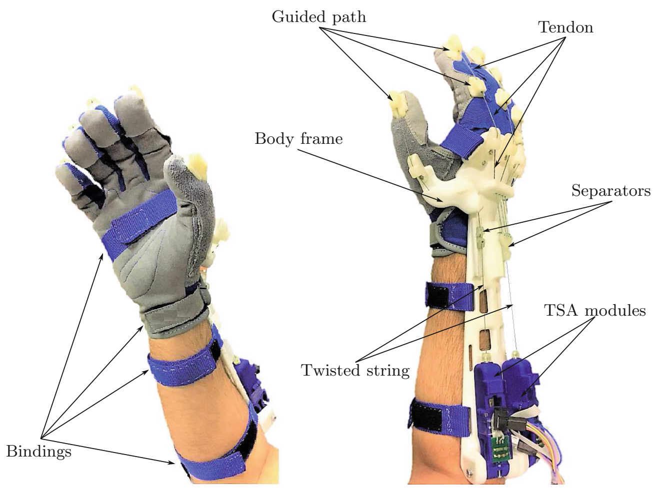


**Fig. 2.** Overview of the ExoTen-Glove.

## 2.2 Design of the ExoTen-Glove

Figure 2 demonstrates a simple and light-weight haptic ExoTen-Glove that has been designed to be worn comfortably without any external bulky mechanism to drive the fingers by tendon-based actuation using the skeleton structure of the fingers that fully supports the full motion of the human fingers. It consists of a rigid supporting frame with anatomical shape of forearm made of Polyamide (PA 12) by Laser Sintering (SLS), a soft glove, two independent TSA module to drive a group of fingers from index to little finger and the thumb separately for grasping tasks and tendon guided path. A comfortable soft glove have been used to be worn by user and the fingers are connected to the TSA module by means of tendons (Dyneema 0.26 mm) that are guided through a path made of semi-soft material 3D printed (EFLEX) attached on the glove and a linear guide to prevent the twisting of the strings itself and with a separator to guide the tendons trough each finger. The path is designed with a curved shape to allow the tendons follow the finger movement with its anatomical shape and prevent the shear forces to the attachment points. In order to prevent the slack in top of the fingers, we used binding structure for tightening the glove on top of the fingers. Since the users have different finger length, we can adjust the length of the tendons by twisting the tendon on each finger. The total weight of the ExoTen-Glove is approximately 360 g.

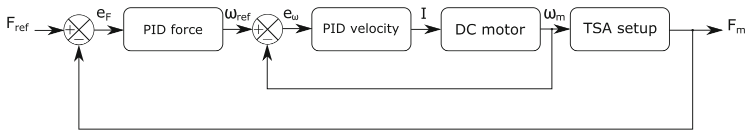


**Fig. 3.** Block diagram of the TSA's force and velocity control loop. Subscripts $ref$ and $m$ denotes reference and measured, respectively. Meanwhile $F$, $\omega$, $I$ and $e$ represents force, velocity, current, and error respectively.

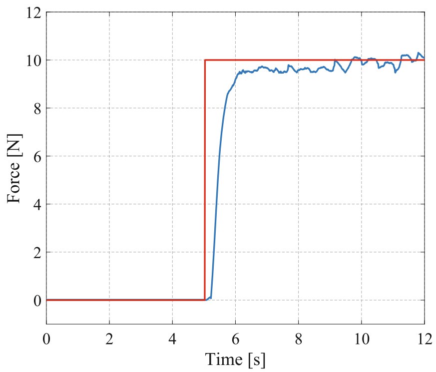


**Fig. 4.** The step response of the TSA force controller. The control bandwidth is approximately 2 rad/s.

## 2.3 Electronics

The electronics unit consists of a STM32F4 32-bit microcontroller and an L298-based Arduino motor driver. The design choice was made by considering the performance of the overall system while keeping the cost affordable. The microcontroller performs signal processing and control algorithm calculation including the ADC measurements as well as velocity and force control. Communication between the microcontroller and the PC is established through a serial USB communication.

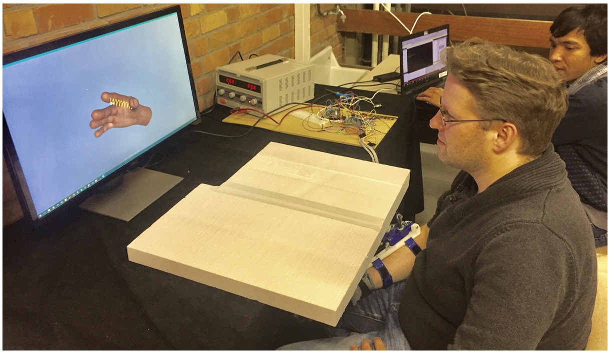

**Fig. 5.** The experimental setup. In this experiment participants were asked to wear the ExoTen-Glove and squeeze a set of virtual springs with different stiffness by their thumb and index finger while the ExoTen-Glove were covered.

### 2.4 Controller

The TSA is controlled with a cascaded PID controller structure whose diagram is shown in Fig. 3. The outer loop regulates the force with a slower frequency of 1 kHz. Meanwhile the inner loop controls the DC motor velocity with a faster 5 kHz frequency. To reduce the ADC noise, the measured force is filtered with a low pass filter. Its parameter is chosen such that the trade-off between delay and noise level is balanced.

The PID gains are tuned by examining the dynamic responses upon applying step force references. For a satisfactory force tracking, a time constant of at least 0.5 s is desired. The step response of the controller is shown in Fig. 4. As evident from the plot, there is still some oscillatory behavior during the steady state phase. This is mostly due to the force sensor noise which is not filtered out entirely. Nevertheless, the noise level is still within tolerance and the rise time satisfies our requirement.

## 3 Experimental Evaluation

### 3.1 Subjects

A total of 8 healthy right-handed participants (6 males and 2 females) took a part in the experiment with an average age of 30 years (ranging from 24 to 36 years old) with normal or corrected to normal vision, no disorder of touch and no history of neurological or psychiatric condition. Each experiment took around 30 min for each participant and he/she was informed about the general goal of the research. Each participant was fully debriefed and was given the opportunity to ask questions and to comment on the research after the experiment.

### 3.2 Material and Apparatus

We employed the TSA based ExoTen-Glove for the experiments. This novel device is the first test-bed for twisted string based haptic glove. The tracking of the finger movement and force feedback are provided through TSA system. It provides one Degrees of Freedom (DOF) motion for each finger and it can render high forces in grasping without instability. The system is lightweight and enable transparent interactions with virtual reality making realistic grasping manipulations possible. The participants were seated at a table and wore the glove in their right hands. The fingers were positioned in the ExoTen-Glove as shown in Fig. 5 and finger movements and interactions with virtual objects were presented on a computer screen. In order to increase the immersion during the experiment, subjects real hands were covered and subjects were informed to focus on the virtual hand. The experiments were done using a desktop PC (Intel i7-6820 HQ Quad-Core CPU with 2.7 GHz, 16 GB of Ram, with Intel HD Graphics 530 processor). An open source platform, CHAI3D, and a set of C++ libraries were used for the modeling and for simulating the haptics, and for visualization of the virtual world. A virtual world with a virtual hand and spring was developed, see Fig. 6. CHAI3D platform supports several commercial haptic devices and it is possible to extend it to support new custom force feedback devices. We have extended this platform by adding the drivers and libraries of our custom-made haptic glove.

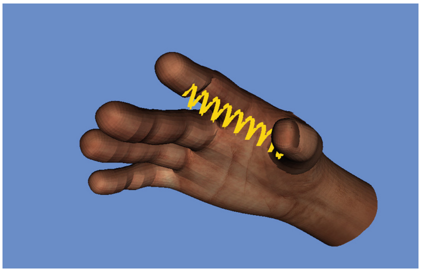

**Fig. 6.** The virtual hand and spring which was used in this experiment. (Color figure online)

### 3.3 Experiment Procedure

In this experiment participants were asked to wear the ExoTen-Glove and squeeze a virtual spring with different stiffness by their index and thumb finger aiming to distinguish the stiffness of different virtual springs. The participants were instructed to maintain their right arm on a fixed position. They were asked to complete a task for which instructions were given prior to testing. We implemented eight sets of experimental tasks [26]. In each sets we introduced two spring with different stiffness identifying with color of red and yellow and in each sets stiffness of the springs was chosen randomly. The chosen pair of spring's stiffness are as follow: 2–3, 2–4, 2–5, 2–6, 6–7, 6–8, 6–9, 6–10 N/mm (The order of the stiffness sets during the experiment was chosen randomly for all users). As it was expected, the users would have higher difficulty in distinguishing spring stiffness as their differences become smaller. In the stiffness experiments, the index finger started from a fully open position to a predefined closed position. This enabled the virtual spring between the fingers to be compressed the same amount. Participants presented with a virtual spring and allowed to squeeze it until they are sure about their response.

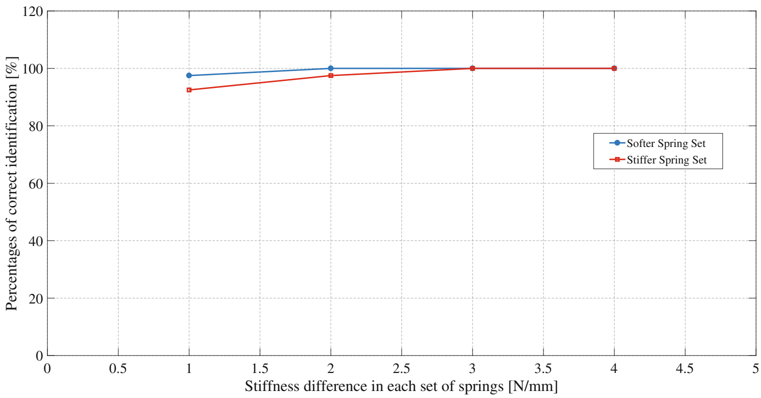


**Fig. 7.** Percentage of correct identification with respect to stiffness differences for two sets of stiffness.

### 3.4 Analysis and Results

For stiffness evaluation different experiments are used in the literature [25]. One the commonly used method is Weber Fraction for the characterization of human perception of stiffness. As Weber Fraction is dimensionless; individual performance can be compared with different quantities of force ($N$) or stiffness ($N/m$) [25]. In this experiment, a similar experiment design of two-alternative forced choice method is implemented as in Blake et al. [26] rather than Weber Fractions due to forced choice methods simplicity in the design and analysis.

### 3.5 Discussion

In the present study, a light-weight and compact wearable haptic glove (ExoTen-Glove) based on TSA was presented. The ExoTen-Glove was evaluated by a stiffness difference evaluation experiment. In this experiment, the subjects squeezed two virtual springs with their thumb and index finger. The aim was to find out how well they could differentiate the stiffness differences of two springs with a TSA based ExoTen-Glove. We expected that the users would have difficulty in distinguishing when the stiffness difference got smaller. Our results showed that ExoTen-Glove based on TSA system improved stiffness differentiation task significantly for the high and low spring stiffness and users were able to distinguish virtual spring stiffness differences easily with high accuracy.

Previous studies showed that small stiffness difference cases reported to be near the limit of perception. As the probability of a correct answer by simply guessing is 50%, Blake et al. [26] concluded that in the cases of small difference of soft stiff springs, the users did not receive clear enough information from the haptic glove to be able to distinguish the virtual springs. The result of the present study illustrated that users were able to distinguish small stiffness differences such as 2 and 3 N/mm easily and significantly higher than the previous studies (See Fig. 7). Furthermore, participants percentage of correct responses for the softer spring and the stiffer spring are high. Thereby, the present study extended the previous study [26] and illustrated the advantage of TSA system in stiffness evaluation.

## 4 Conclusions

This paper presented a compact haptic glove based on TSA system for virtual reality. One of the main challenge in wearable haptic glove research is to design an actuator that is small and compact enough to be worn and at the same time powerful enough for enabling stable and high force feedback to the fingers during grasping virtual objects. Haptic glove based on TSA system has the advantage of a simple design and light-weight actuators in comparison with other tendon-based haptic gloves. Even though using TSA system has many advantages such as low-cost, compact design and high force output, it has a main disadvantages, that is its lifetime. Our presented ExoTen-Glove uses Dyneema tendon for the twisted string actuators and also as a tendon guide through a path made of a semi-soft material (EFLEX) for the finger movements. In the future, different tendon's materials with higher lifetime and lubrication at the tendon could be used to increase its lifetime.

The ExoTen-Glove is evaluated by stiffness experiments. In this experiment, users squeezed a virtual spring with their thumb and index fingers. The aim of the study is to illustrate the benefit of using TSA system in distinguishing stiffness of a pair of virtual springs. As illustrated in the previous studies [26] it is expected the users would have higher difficulty in distinguishing spring stiffness as their differences become smaller. Our results confirmed and extended previous findings. Users were able to identify the spring stiffness with higher percentage of accuracy compared to the previous studies [26]. In the current ExoTen-Glove, grasping a simple object, spring with different stiffness, using index and thumb was demonstrated and experimental results show the advantages of TSA system in stiffness perception and grasping tasks.

Currently, we are working on the next version of the ExoTen-Glove to reduce its weight and cost with implementing a smaller actuation module and using lower cost DC motors and custom-made encoders, adding composite linkages for increasing realism of haptic feedback instead of using a glove. Additionally, we are integrating HTC VIVE headset and Unity game engine into CHAI3D platform for complex hand animations with haptic feedback to increase the realism and immersion of the VR and advanced model based controls. In the future, the haptic glove will be extended for more complex grasping tasks by adding independent actuators for each fingers and controlling them separately for rehabilitation (ExoTen-Hand) and haptic purposes (ExoTen-Glove).

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