FlexTorque: Exoskeleton Interface for Haptic Interaction with the Digital World

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Abstract. We developed a novel haptic interface FlexTorque that enables realistic physical interaction with real (through teleoperation system) and Virtual Environments. The idea behind FlexTorque is to reproduce human muscle structure, which allows us to perform dexterous manipulation and safe interaction with environment in daily life. FlexTorque suggests new possibilities for highly realistic, very natural physical interaction in virtual environments. There are no restrictions on the arm movement, and it is not necessary to hold a physical object during interaction with objects in virtual reality. Because the system can generate strong forces, even though it is light-weight, easily wearable, and intuitive, users experience a new level of realism as they interact with virtual environments.

Keywords: Exoskeleton, haptic display, haptic interface, force feedback, Virtual Reality, game controller.

1 Introduction

In order to realize haptic interaction (e.g., holding, pushing, and contacting the object) in virtual environment and mediated haptic communication with human beings (e.g., handshaking), the force feedback is required. Recently there has been a substantial need and interest in haptic displays, which can provide realistic and high fidelity physical interaction in virtual environment. The aim of our research is to implement a wearable haptic display for presentation of realistic feedback (kinesthetic stimulus) to the human arm. We developed a wearable device FlexTorque that induces forces to the human arm and does not require holding any additional haptic interfaces in the human hand. It is completely new technology for virtual and augmented environments that allows user to explore surroundings freely. The concept of Karate (empty hand) Haptics proposed by us is opposite to conventional interfaces (e.g., Wii Remote [1], SensAble's PHANTOM [2]) that require holding haptic interface in the hand, restricting thus the motion of the fingers in midair.

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The powered exoskeleton robots, such as HAL [3] (weight of 23 kg) and Raytheon Sarcos [4] (weight of about 60 kg) intended for the power amplification of the wearer can be used for the force presentation as well. However, they are heavy, require high power consumption, and pose danger for user due to the powerful actuators.

The compact string-based haptic device for bimanual interaction in virtual environment was described in [5]. The users of SPIDAR can intuitively manipulate the object and experience 6-DOF force feedback. The human-scale SPIDAR allowing enlargement of working space was designed [6]. However, the wires moving in front of the user present the obstacle for the human vision. They also restrict the human arm motion in several directions and user has to pay attention to not injure himself. Moreover, user grasps the ball-shaped grip in such a way that fingers cannot move.

2 Development of Haptic Interface FlexTorque

In order to achieve human-friendly and wearable design of haptic display, we analyzed the amount of torque to be presented to the operator arm. Generally, there are three cases when torque feedback is needed. The first case takes place when haptic communication with remote human needs to be realized. For example, the person handshakes the slave robot and joint torques are presented to the operator. Such interaction results in very small torque magnitude (in the range of 0-1.5 Nm). The second situation takes place when slave robot transports heavy object. Here, the torque values are much higher than in previous case and torque magnitude depends on the load weight. However, continuous presentation of high torques to the operator will result in human muscle fatigue. We argue that downscaled torque indicating direction of the force would be informative enough. The third and the worst case of contact state in term of interactive force magnitude is collision. The result of collision with fixed object (as it is often the case) is immediate discontinuation of the operator's arm motion. Therefore, the power of torque display must be enough to only fixate the operator arm.

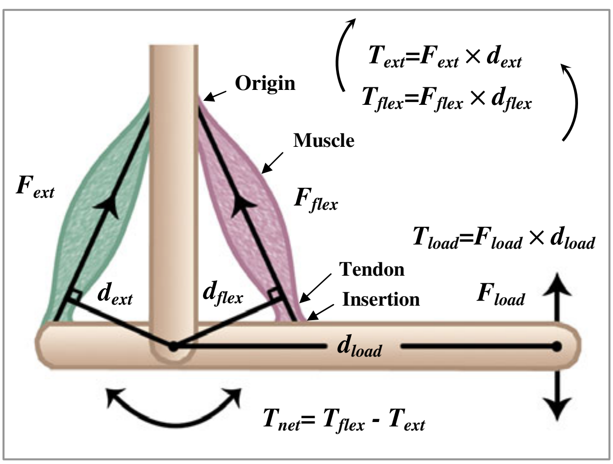

Fig. 1. Structure and action of a skeletal muscle

The idea behind novel torque display **FlexTorque** (haptic display that generates **Fl**exor and **ex**tensor **Torque**) is to reproduce human muscle structure, that allows us to perform dexterous manipulation and safe interaction with environment in daily life. Main functions of the muscles are contraction for locomotion and skeletal movement [7]. Muscle is connected to the periosteum through tendon (connective tissue in the shape of strap or band). The muscle with tendon in series acts like a rope pulling on a lever when pulling tendons to move the skeleton (Fig. 1).

Because muscles pull but cannot push, hinge joints (e.g. elbow) require at least two muscles pulling in opposite direction (antagonistic muscles). The torque produced by each muscle at a joint is the product of contractile force (F) and moment arm at that joint (d). The net torque T_{net} is the sum of the torques produces by each antagonistic muscle. Movement of human limbs is produced by coordinated work of muscles acting on skeletal joints. The structure of the developed torque display FlexTorque and the detailed view of the driving unit of haptic display are presented in Fig. 2.

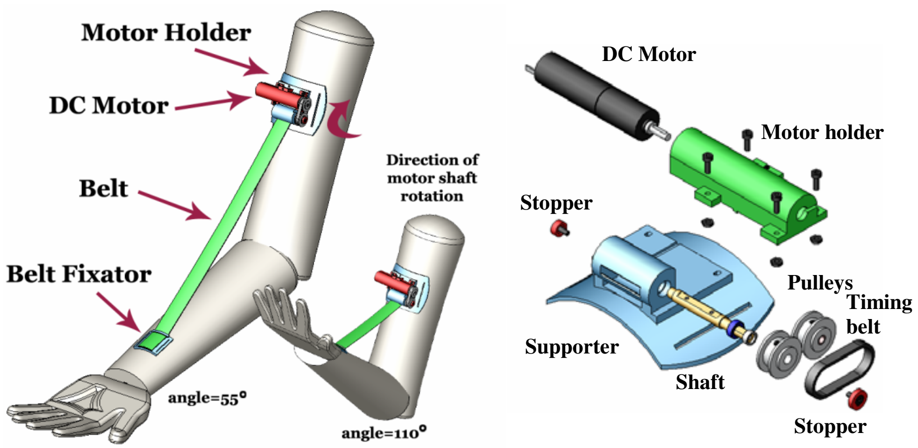

Fig. 2. FlexTorque on the human's arm surface and 3D exposed view of the driving unit

FlexTorque is made up of two DC motors (muscles) fixedly mounted into plastic Motor holder unit, Belts (tendons), and two Belt fixators. The operation principle of the haptic display is as follows. When DC motor is activated, it pulls the belt and produces force F_{flex} generating the flexor torque T_{flex}. The oppositely placed DC motor generates the extensor torque T_{ext}. Therefore, the couple of antagonistic actuators produce a net torque at operator elbow joint T_{net}. We defined the position of the Insertion point to be near to the wrist joint in order to develop large torque at the elbow joint.

Let us consider the calculation procedure of the net torque value. The layout of the forces and torques applied to the forearm during flexion is given in Fig. 3.

The tension force F_t of the belt can be derived from:

$$F_t = \frac{T_m i}{r}, \quad (1)$$

where T_m is the motor torque, i is the gear ratio, and r is the shaft radius.

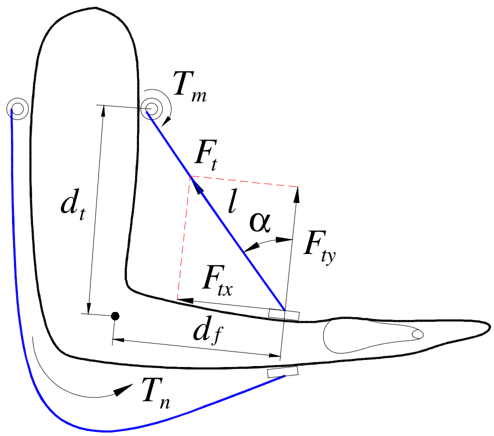

Fig. 3. Diagram of applied forces and torques

The net torque T_n acting at the elbow joint is:

$$T_n = F_{ty} d_f = F_t d_f \cos(\alpha), \tag{2}$$

where d_f is the moment arm.

The angle α varies according to the relative position of the forearm and upper arm. It can be found using the following equation:

$$\alpha = \cos^{-1}\left(\frac{l^2 + d_t^2 - d_f^2}{2ld_t}\right), \tag{3}$$

where d_t is the distance from the pivot to the Origin; l is the length of belt, it can be calculated from the rotation angle of the motor shaft.

The biceps actuator of FlexTorque is capable of producing the net torque at the elbow joint as high as 8.0 Nm (Maxon motor RE 13, Stall torque of 8.52 mNm, Gearhead reduction ratio of 17:1). Each unit is compact and extremely light weight (61 g). This was achieved due to the use of plastic and duralumin materials in manufacturing the main components. The Supporter surface has concave profile to match the curvature of human arm surface (Fig. 4).

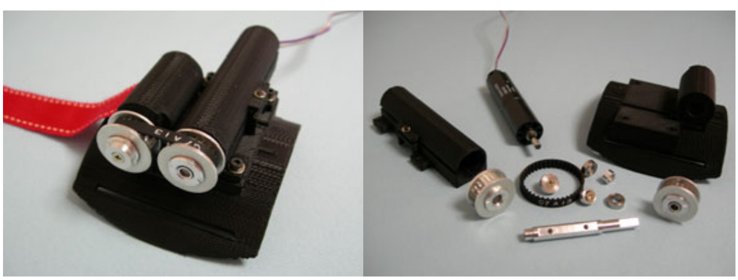

Fig. 4. Manufactured driving unit of FlexTorque

The essential advantage of the structure of FlexTorque device is that heaviest elements (DC motors, shafts, and pulleys) are located on the part of upper arm, which is nearest to the shoulder. Therefore, operator's arm undergoes very small additional loading. The rest of components (belts, belt fixators) are light in weight and do not load the operator's muscles considerably. We propose to use term "Karate (empty hand) Haptics" to such kind of novel devices because they allow presenting the forces to the human arm without using additional interfaces in the human hands. The developed apparatus features extremely safe force presentation to the human's arm. While overloading, the belt is physically disconnected from the motor and the safety of the human is guaranteed.

3 Applications

The main features of FlexTorque are: (1) it presents high fidelity kinesthetic sensation to the user according to the interactive forces; (2) it does not restrict the motion of the human arm; (3) it has wearable design; (4) it is extremely safe in operation; (5) it does not require a lot of storage space. These advantages allow a wide range of applications in virtual and augmented reality systems and introduce a new way of game playing. A number of games for augmented sport experiences, which provide a natural, realistic, and intuitive feeling of immersion into virtual environment, can be implemented.

Haptic interface FlexTorque was demonstrated at SIGGRAPH ASIA 2009 [8]. We designed three games with haptic feedback. We developed the Gun Simulator game with the recoil imitation and Teapot Fishing game with haptic presentation of the rod tug when fish bites. The virtual biceps curl exercise machine was designed. With Virtual Gym game we can do the strength training exercise at home in a playful manner (Fig. 5). The belt tension creates the resistance force in the direction of the forearm motion. The user can adjust the weight easily.

Wii MotionPlus controller was used in order to capture the complex motion of the user arm. To maintain the alignment of the extensor belt on the elbow avoiding thus slippage, user wears specially designed pad equipped with guides. In total more than 100 persons had experienced novel haptic interface FlexTorque. We have a got very

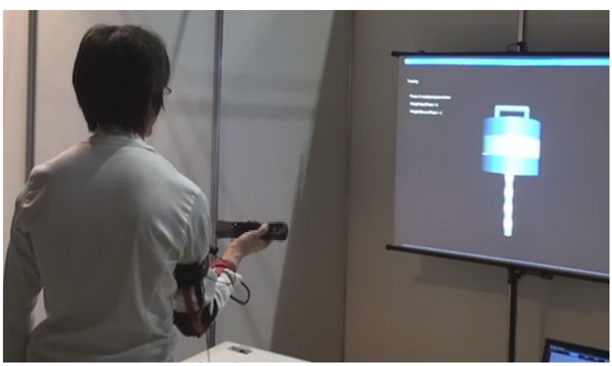

Fig. 5. The Virtual Gym game

positive feedback from the users and companies. While discussing the possible useful applications with visitors, the games for physical sport exercises and rehabilitation were frequently mentioned. The majority of users reported that this device presented force feedback in a very realistic manner.

4 Conclusions and Future Research

Novel haptic interface FlexTorque suggests new possibilities for highly realistic, very natural physical interaction in virtual environments, augmented sport, augmented game applications, and teleoperation.

A number of new games for sport experiences, which provide a natural, realistic, and intuitive feeling of physical immersion into virtual environment, can be implemented (such as skiing, biathlon (skiing with rifle shooting), archery, tennis, sword dueling, etc.). FlexTorque will also enable the presentation of strong vibrations in driving simulator, muscle stiffness, and collision (contact) with a virtual object.

The future goal is to capture the complex movement and recognize the gesture of the user through accelerometers and MEMS gyroscopes integrated into the holder and fixator of the FlexTorque and optical full-body motion capture system. The new version of the FlexTorque (**ExoInterface**) will take advantages of the **Exo**skeletons (strong force feedback) and Wii Remote **Interface** (motion-sensing capabilities and simplicity of usage).

We expect that FlexTorque will support future interactive techniques in the field of robotics, virtual reality, sport simulators, and rehabilitation.

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