ExoInterfaces: Novel Exosceleton Haptic Interfaces for Virtual Reality, Augmented Sport and Rehabilitation

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ABSTRACT
We developed novel haptic interfaces, FlexTorque and FlexTensor that enable realistic physical interaction with real 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.

ACM Classification Keywords
H5.2. Information interfaces and presentation: User Interfaces – haptic I/O, interaction styles, prototyping.

General Terms
Design, Experimentation, Performance.

Keywords
Exoskeleton, haptic display, haptic interface, force feedback, Virtual Reality, augmented sport, augmented games, rehabilitation, 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 the conventional interfaces (e.g., Wii Remote [11], SensAble's PHANTOM [7]) that require holding haptic interface in the hand, restricting thus the motion of the fingers in midair.

The powered exoskeleton robots, such as HAL [3] (weight of 23 kg) and Raytheon Sarcos [8] (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.

Another class of exoskeletons is aimed at teleoperator systems. Most of the force feedback master devices are similar in sizes to slave robot and are equipped with powerful actuators. Such systems pose dangerousness for human operator and in case of failure during bilateral control can harm human. In the last years there have been several attempts to make the force feedback devices more compact, safe, and wearable.

In [5], an exoskeleton-type master device was designed based on the kinematic analysis of human arm. Pneumatic actuators generate torque feedback. The authors succeeded in making the lightweight and compact force reflecting master arm. However, the force-reflection capability of this device is not enough to present contact forces effectively. An artificial pneumatic muscle-type actuator was proposed [4]. Wearable robotic arm with 7 DOF and high joint torques was developed. Robotic arm uses parallel mechanisms at the shoulder part and at wrist part similarly to the muscular structure of human upper limb. It should be noted, however, that dynamic characteristics of such pneumatic actuator possess strong nonlinearity and load-dependency, and, thus, a number of problems need to be resolved for its successful application.

The compact string-based haptic device for bimanual interaction in virtual environment was described in [6]. 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 [9]. However, the wires moving in

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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.

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 a 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. For the case of collision with movable obstacle, the haptic display should induce human's arm motion in the direction of the impact force, decreasing thus the possible damages.

2. DEVELOPMENT OF THE HAPTIC DISPLAY FlexTorque

The idea behind the 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.

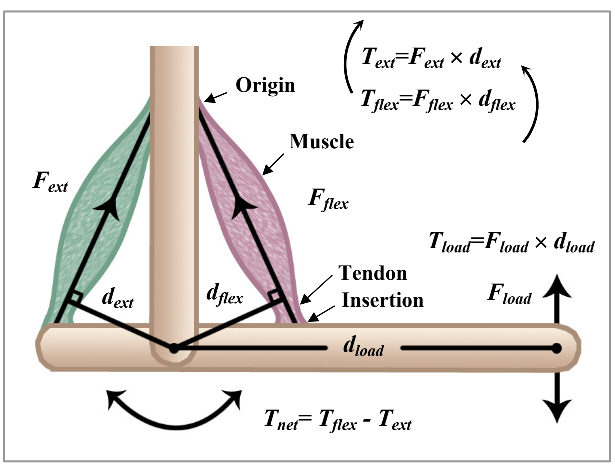

Figure 1. Structure and action of a skeletal muscle.

Main functions of the muscles are contraction for locomotion and skeletal movement. A muscle generally attaches to the skeleton at both ends. Origin is the muscle attachment point to the more stationary bone. The other muscle attachment point to the bone that moves as the muscle contracts is Insertion. 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 (Figure 1).

When we hold a heavy object in a palm, its weight produces torques in the wrist, elbow, and shoulder joint. Each muscle generates a torque at a joint that is the product of its contractile force and its moment arm at that joint to balance gravity force, as well as inertial forces, and contact forces. Thus, we can feel object weight.

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 is presented in Figure 2.

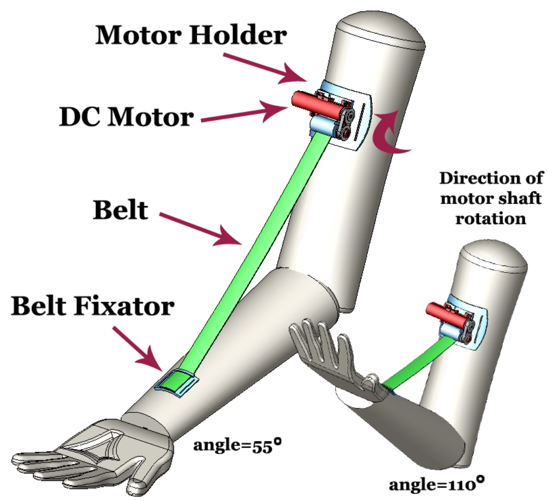

Figure 2. FlexTorque on the human's arm surface.

FlexTorque is made up of two DC motors (muscles) fixedly mounted into plastic Motor holder unit, Belts (tendons), and two Belt fixators (Insertions). 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.

The position of the operator's arm, when flexor torque is generated, is shown in Figure 3 (where θ stands for angle of forearm rotation in relation to upper arm).

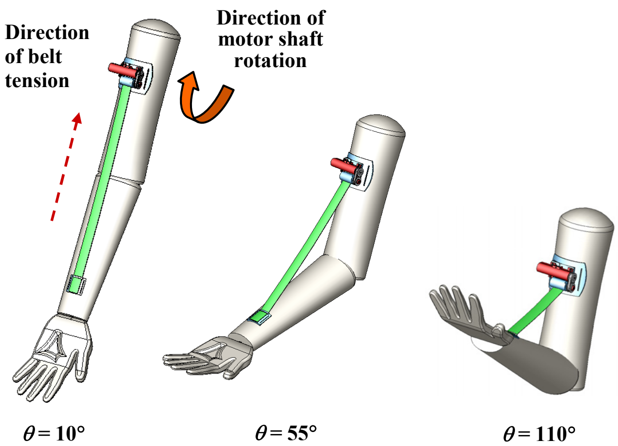

Figure 3. Positions of the human's arm under flexor torque.

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 Figure 4.

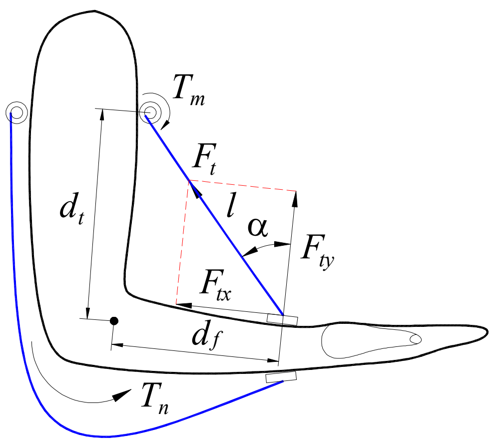

Figure 4. Diagram of applied forces and torques.

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

$$F_t = \frac{T_m i}{r}, \tag{1}$$

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

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:

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

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 detailed view of the FlexTorque is presented in Figure 5.

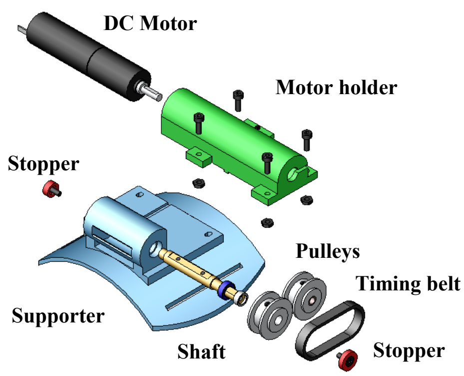

Figure 5. 3D exploded view of the driving unit of FlexTorque.

Each unit is compact and light in weight (60 grams). 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 (Figure 6).

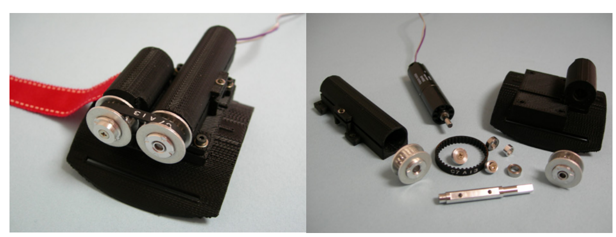

Figure 6. Driving unit of FlexTorque.

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.

The vibration of the human arm (e.g., simulation of driving the heavy truck) can be realized through alternate repeatable jerks of torque of antagonistic motors. Thus, the operator can perceive the roughness of road surface.

The FlexTorque enables the creation of muscle stiffness. By contracting belts before the perturbation occur we can increase the joint stiffness. For example, during collision of human hand with the moving object in Virtual Environment the tension of the belt of one driving units drops abruptly and the tension of the belt pulling the forearm in the direction of the impact force increases quickly.

The contact and collision with virtual object can be presented through FlexTorque as well. In the case of collision, the limb must be at rest. In such a case, the net torque produced by the muscles is opposed by another equal but opposite torque T_{load}. Similarly to the human muscles, the net torque produced by the haptic display restrains the further movement of the user's arm.

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.

Here we summarize the possible application of haptic display FlexTorque:

1) Virtual and Augmented Environments (presentation of physical contact to human's arm, muscle stiffness, object weight, collision, physical contact, etc.).
2) Augmented Sport and Games (enhancing the immersive experience of the sport and games through the force feedback).
3) Rehabilitation (user with physical impairments can easily control the applied torque to the arm/leg/palm during performing the therapeutic exercises).
4) Haptic navigation for blind persons (the obstacle detected by camera is transferred to force restricting the arm motion in the direction of the object).

A number of games for augmented sport experiences, which provide a natural, realistic, and intuitive feeling of immersion into virtual environment, can be implemented. The Arm Wrestling game that mimics the real physical experience is currently under development (Figure 7). The user wearing FlexTorque and Head mounted display (HMD) can play either with a virtual character or a remote friend for more personal experience. The virtual representation of players' arms are shown on the HMD. While playing against a friend, user sees the motion of arms and experiences the reaction force from rival.

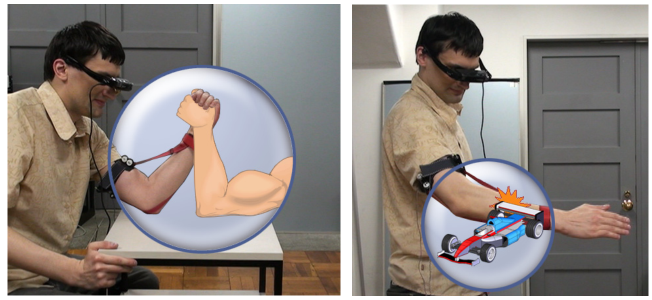

Figure 7. Augmented Arm Wrestling and Augmented Collision.

4. USER STUDY AND FUTURE RESEARCH

FlexTorque haptic interface was demonstrated at SIGGRAPH ASIA 2009 [1,2,10]. To maintain the alignment of the extensor belt on the elbow avoiding thus slippage, user wears specially designed pad equipped with guides.

We designed three games with haptic feedback. We developed the Gun Simulator game with the recoil imitation (Figure 8). Quick single jerk of the forearm simulates the recoil force of a gun. High-frequency series of impulsive forces exerted on the forearm imitate the shooting by machine gun. In this case upper motor is supplied with short ramp impulses of current.

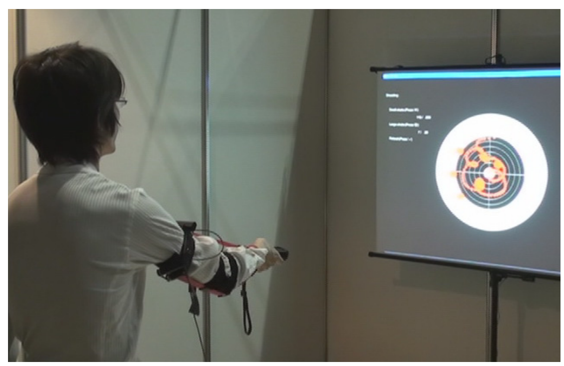

Figure 8. The Gun Simulator game.

In Teapot Fishing game player casts a line by quick flicking the rod towards the water (Figure 9).

Figure 9. The Teapot Fishing game.

Once the user feels the tug at the forearm (and see float going down), he gives fishing rod a quick jerk backward and up. When jerk is late, the fish (teapot) gets off the hook. The ramp impulse of the motor torque generates the jerk of the forearm downward indicating that fish picks up the hook. Such practice can help the user to get a feel of the real fishing.

With Virtual Gym game we can do the strength training exercise at home in a playful manner (Figure 10). The virtual biceps curl exercise machine was designed. The belt tension creates the resistance force in the direction of the forearm motion. The user can adjust the weight easily.

Figure 10. The Virtual Gym game.

In total more than 100 persons had experienced novel haptic interface FlexTorque. We have a got very 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.

5. DESIGN OF MULTIPURPOSE HAPTIC DISPLAY FlexTensor

The motivation behind the development of the **FlexTensor** (haptic display that uses **Flex**ible belt to produce **Tens**ion f**or**ce) was to achieve realistic feedback by using simple and easy to wear haptic display.

The multipurpose application is realized by means of fixation of different elements of FlexTensor (i.e. middle of the belt, Origin/Insertion points) in the particular application. The structure of the FlexTensor is similar to the flexor part of FlexTorque haptic display. The main differences are: (1) belt connects the movable points on the human arm; (2) both attachment points of the belt have embedded DC motors.

In the haptic display FlexTorque the function of each attachment point is predetermined (Figure 11). The configuration of FlexTensor allows each point to perform the function of Insertion and Origin depending on the purpose of application (Figure 12). This fact enables to enlarge the area of FlexTensor applications in Virtual Reality extraordinary.

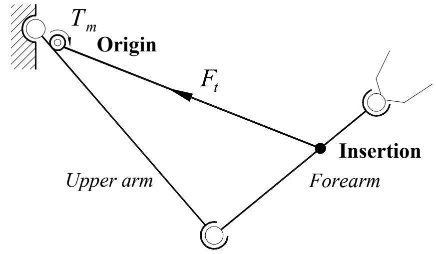

Figure 11. Kinematic diagram of FlexTorque and human arm.

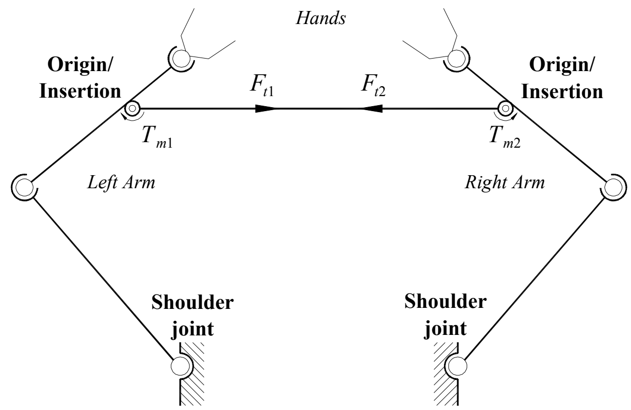

Figure 12. Kinematic diagram of FlexTensor and human arm.

In the configuration when the middle of the belt is not fixed, FlexTensor presents the external force resisting the expanding of the human arms (basic configuration). This action can be used for simulation of the breaststroke swimming technique, when human sweeps the hands out in water to their widest point (Figure 13). The configuration, in which the middle of the belt is fixed by user standing on the band with both (or one) feet, enables presentation of the object weight (Figure 14). The tension of the belt represents the magnitude of gravity force acting on the human arms. The fixation of the middle of the belt can be positioned on the human neck (for simulation of human arm lifting) and on the waist (for simulation of resistance of environment in the direction of arm stretching, e.g., in the case of contact with the virtual wall).

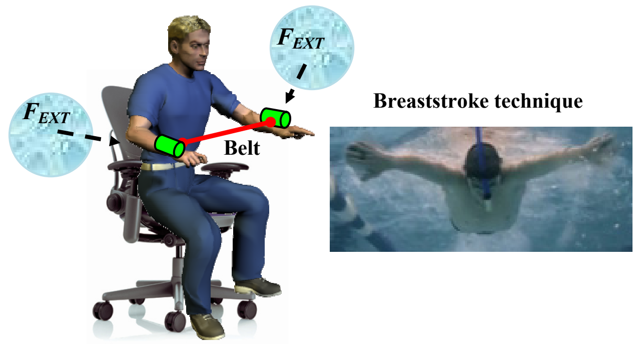

Figure 13. Application of FlexTensor for swimming training.

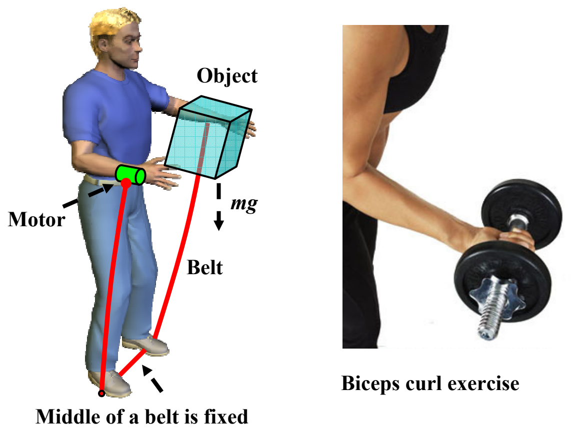

Figure 14. Application of FlexTensor for the weight presentation and strength training exercise.

In the case when the palm of one arm is placed on some part of the body (e.g., waist, neck), this attachment point becomes Origin. Such action as unsheathing the sword can be simulated by stretching out the unfixed arm. FlexTensor can interestingly augment the 3D archery game presenting the tension force between arms.

The illusion of simultaneous pulling of both hands can be implemented by exertion of different values of forces F_{t1} and F_{t2} in the basic configuration (see Figure 12). The illusion of being pulled to the left side and to the right side can be achieved when $F_{t1}>F_{t2}$ and $F_{t1}<F_{t2}$, respectively.

The developed apparatus features extremely safe force presentation to the human's arm. While overloading, physical disconnection of the belt from the motor protects the user from the injury.

6. CONCLUSIONS

Novel haptic interfaces FlexTorque and FlexTensor suggest new possibilities for highly realistic, very natural physical interaction in virtual environments, augmented sport, and augmented game applications.

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, driving simulator, etc.).

The future goal is the integration of the accelerometer and MEMS gyroscopes into the holder and fixator of the FlexTorque and into FlexTensor for capturing the complex movement and recognizing the gesture of the user. The new version of the FlexTorque and FlexTensor (**ExoInterface**) will take advantages of the **Exo**skeletons (strong force feedback) and Wii Remote **Interface** (motion-sensing capabilities).

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

7. ACKNOWLEDGMENTS

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