Evaluating Virtual Embodiment with the ALEx Exoskeleton

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Abstract. The assessment of virtual embodiment has focused primarily on experimental paradigms based on multisensory congruent cues, such as auditory, tactile, visual and motor, mainly due to the technological limitations of haptic feedback. In this work virtual embodiment in an avatar is assessed by means of a new lightweight exoskeleton (ALEx) with a focus on the perception of danger and aggressive behavior. In particular an experiment has been designed assessing the effectiveness of haptic feedback while interacting with an opponent avatar. Experiments are evaluated based on physiological measures and questionnaires.

1 Introduction

Body awareness sensation is a central topic of recent research in Virtual Reality, because it is strongly related with immersivity and it can be experimentally manipulated allowing to investigate key questions in body representation and ownership. Through Virtual Reality the subject can experience situations that are not possible in the real world [10]. Starting from the foundational results in rubber hand illusion, research has explored whole body substitutes, that can have temporary effects on subject attitudes [11]. In particular full body illusions allow to transfer the subject in another body experiencing situations that challenge the usual role and behavior the subject [8].

This work addresses the case of perceiving aggressive behavior through a virtual environment comparing pure visual stimuli with visuo-haptic stimuli. The haptic stimuli are provided through the ALEx arm exoskeleton that, given its workspace and dynamic capabilities, allows to simulate the interaction of the subject's avatar with an aggressive virtual human. Avatars of the subject, and in general virtual characters, have been extensively used in literature for studies in Virtual Reality, as tools for experimental psychology with applications in the social domain or for cognitive rehabilitation. Limited research, however, has been performed on the haptic interaction of users with virtual characters, with few notable exceptions. An example is a SPIDAR-like system [6] for boxing practice that allows to haptically interact with an opponent. The range of force and the nature of motion are anyway limited given the type of haptic interface. A different type of approach involves vibrotactile feedback, based mainly on arrays of

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actuators as in [2] for training and in [12] for virtual body ownership assessment. The present work adopts a new Virtual Human engine specifically designed for the integration with robotic system allowing to easily map the robotic kinematics with the Virtual Human kinematic, together with the exchange of forces between the different simulation elements. These features can be compared with the overview of existing engines provided by Gillies [5].

2 Materials and Methods

This section discusses the experiments presenting first the materials comprising the ALEx exoskeleton and the Virtual Environment system adopted for the experiment. Then the methods are discussed presenting the experimental protocol and the measures performed.

2.1 Virtual Environment

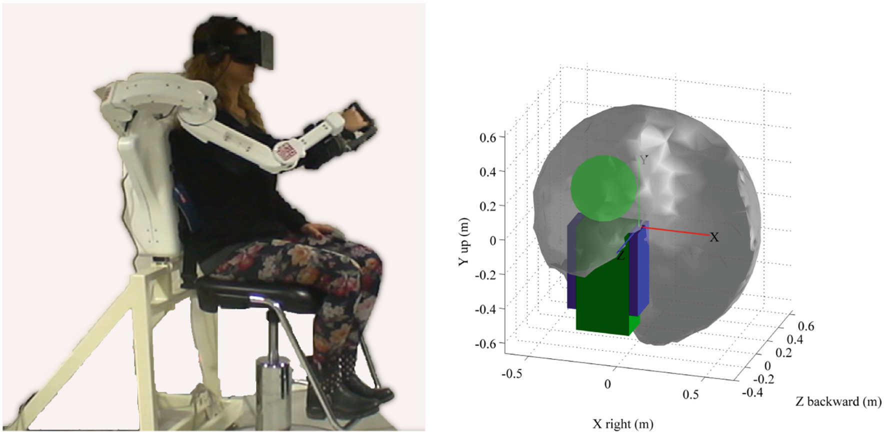
The Virtual Environment adopted for the experiment is composed of three elements: (1) an ambient scene, depicting a dead-ended street of about 5 by 5 m, with some objects on the ground, low lighting conditions and fog; (2) two virtual characters, one representing the subject of the experiment, the other the opponent; (3) a mirror in front of the subject used for familiarization.

The graphic display is based on the Oculus Rift HMD with a per-eye resolution of 800×640 at 60 Hz with a FOV of 90 degrees. The chosen HMD has a good inertial head tracking that improves co-location and immersiveness allowing the user to visually explore the virtual body with minimal perceived drift.

The overall experimental setup is shown in Fig. 1(a).

2.2 ALEx Exoskeleton

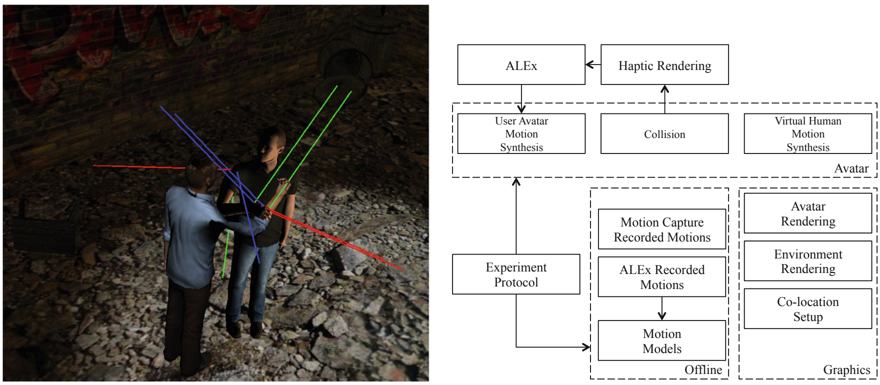
The haptic interaction is provided by means of the ALEx arm exoskeleton [1]. This exoskeleton relies on the experience of previous research exoskeleton like the L-EXOS [3], improving it in several ways. ALEx is an upper limb mechanically compliant exoskeleton with low encumbrances, and low friction of the actuation system. ALEx has 6 DOF, 4 of which are actuated (3 in the shoulder, 1 at the elbow). Sensing is provided at rates up to 1 kHz providing end-effector and joints' position and velocity. The control of the exoskeleton is based on an active control of the mechanical impedance of the exoskeleton. Proper sensorization of the tendon transmission allows to implement a series elastic actuator schemes. In the experiment discussed in this paper two control modalities are employed: in the passive modality the subject moves the arm, and the exoskeleton tracks transparently providing gravity compensation, and, if needed motion viscosity. The exoskeleton has a maximum continuous force in the worst condition of 50 N, and a peak force of 100 N. The maximum stiffness at the end-effector is 2 N/mm, while the maximum velocity at the joints is 160 deg/s.



(a) Immersive setup used for the experiment. The subject is seated wearing the Oculus HMD and the ALEx exoskeleton

(b) Workspace of the ALEx exoskeleton depicted in gray, and a block representation of subject torso, arm and head . The origin reference system is on the subject's shoulder.

Fig. 1. Immersive setup and workspace



(a) Snapshot of the environment used for the interaction, showing the user avatar and the opponent avatar.

(b) Software architecture of the system used for the experiment

Fig. 2. Environment and avatar interaction

In the active modality the motion of the exoskeleton is externally controlled through waypoints that can be specified as joint variables or end-effector pose. In this modality each joint is attracted to the target joint value with a virtual spring and limited by maximum joint velocity. In the experiment the stiffness is 200 Nm/rad, and the maximum joint velocity is 52 deg/s. Given the kinematic model the device workspace is shown in Fig. 1(b) where the origin is placed at the shoulder with the axis X running right, Y upward and Z backward.

2.3 Virtual Human Engine

The software architecture is shown in Fig. 2(b), depicting the different involved modules: the experiment protocol manages the different elements of the applications, mainly the interaction of the different Virtual Humans present in the scene. The exchanges of forces and trajectories generated by the Avatar engine are then sent to the ALEx control. The graphical part of the application is based on a haptic enabled VR system [9] enhanced with a Virtual Human engine specifically designed for applications involving Virtual Embodiment through robotic interfaces. The graphical appearance of the Virtual Humans is provided by models in Cal3D format and then skinned by means of GPU.

The point of view of the subject through the HMD has been placed in the location of the head of the avatar, connecting the rotation of the HMD with the one of the virtual head. This allowed the subject to increase the body ownership when looking in the virtual mirror.

The engine associates a Denavit-Hartenberg kinematics to each Virtual Human allowing the resolution of kinematic problems on the upper limbs, and the direct mapping with the ALEx kinematics. The engine supports two types of motion synthesis for the Virtual Human, both employed for the present experiment. The first is based on kinematic recordings with the ALEx exoskeleton: a kinematic recording contains the joint states recorded at 100 Hz and it can be played back by the exoskeleton control system. The resulting virtual path is haptically rendered as a haptic guide with stiffness and damping. By means of the kinematic mapping the exoskeleton recording is mapped to the subject avatar. The other type of motion synthesis is based on motion capture recordings, as the ones expressed in the skeleton format BVH. Finally inverse kinematics is possible for reconstructing the Virtual Human pose.

2.4 Experimental Protocol

The experimental protocol is based on a within-subject 2 factor design: Visual only and Visuo-Haptic. Each subject experienced both the conditions in two sessions that were randomized. The experiment is organized as follows:

1. Phase 1: the subject explores the space moving the arm in the real and virtual space. This phase aims at providing familiarization with the immersive experience. This phase lasts 150 s, then it fades out to black.
2. Phase 2: the attacker appears in front of the subject.

3. Phase 3: the attacker moves the arm of the subject's avatar. In the Visual condition only the avatar of the subject is moved, while in Visuo-Haptic condition also the physical arm of the subject is moved by means of the ALEx exoskeleton. This Phase lasts 1 min. Then the scene fades out.
4. Phase 4: the attacker appears in front of the user again and starts punching the user only with Visual feedback.

In the first session the user performs all the phases with the random selection of the condition of Phase 3, then in the second session only the Phases 2–4 are repeated, using the other condition non selected in the first session.

The motion of the subject's arm during Phase 3 has been obtained by recording the ALEx kinematics from the real case while one actor was moving the arm of another actor wearing the exoskeleton, simulating an aggressive behavior. The first actor was standing in front of the other in the same way of the picture shown in Fig. 2(a). The arm was moved back and forth in front of the second actor in a rapid way. The chosen path leads to an average and a maximum end-effector velocity of 0.2 ± 0.1 m/s and 0.42 m/s respectively, with a range of motion of 42, 14, 8 cm for the x,y and z axis. This corresponds to a maximum joints' velocity of 0.9 rad/s with an average over the 4 joints of 0.23 rad/s. The recording was performed in joint space, and during the playback all the 4 actuated joints of the ALEx were activated to generate the haptic feedback. During the experiment the opponent arm's pose is computed in real-time by solving an inverse kinematic problem using a position in the middle of the subject's arm as target. Conversely, the motion of the attacker used in Phase 4 has been obtained by motion capture using the recording (14,1) of the CMU Motion Capture Database, modified in real-time to target the face of the subject.

2.5 Physiological Measures

The physiological assessment of the experiment has been performed by means of a g-Sensors kit (g-tec, Schiedlberg, Austria) providing measures of Hearth Rate, Electrodermal Activity (EDA, also called Galvanic Skin Response GSR), Respiration Rate and Oxygen Saturation. Among them the EDA is the most important, having shown a linear correlation with the level of subject arousal, for applications of virtual human assessment [4] and embodiment [7].

2.6 Questionnaire

The evaluation questionnaire was aimed at assessing different aspects of the embodied experience. A total of 17 questions were asked for every Session grouped as Control, Presence and Embodiment, and expressed over a 7 point Likert scale. Hereunder we report all the questions details. Presence related questions: P1: "Did the visual aspect of the virtual environment was consistent with the real one?"; P2: "Did the physical aspect of the virtual environment was persuasive?"; P3: "Did the information perceived through your different senses was congruent?"; P4/P7: "In the ending/beginning stage of the experiment, did you have the sensation to actively move your arm?"; P5/P6: "In the ending/beginning stage of the experiment, did you have the sensation to passively move your arm?"; Embodiment related questions: E1: "Did the interaction with the virtual environment was strong or not?"; E2: "Was the interaction with the virtual environment natural or not?"; E3/E4: "In the beginning/ending stage of the experiment, did you perceive a danger sensation?"; E5/E7: "In the beginning/ending stage of the experiment, did you perceive an oppression sensation?"; E6: "In the final phase of the experiment, did you have the sensation that the other avatar could have hit you"; E9: "Did you have the sensation that the other avatar could have grabbed your real arm?";

2.7 Participants

A total of 16 subjects (8 male and 8 female, average age 32 ± 8.5) participated to the experiment. They signed a consent form and all of them had previous experience with games and virtual environments.

3 Experimental Results and Evaluation

Among of all the questions here, for sake of brevity, two main groups associated to the items Presence and Embodiment are presented. In both the plots the average response is presented with the error bars. Wilcoxon test for paired sample has been applied for assessing significativity of differences among sessions. Figure 5 reports the electrodermal response compared across different phases of the sessions and across sessions.

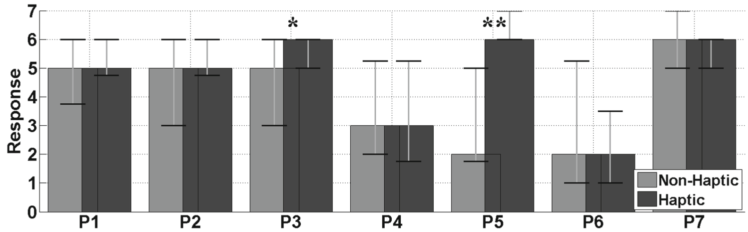


Fig. 3. Presence questions. Bars report the average value with error value. Asterisk means normal and high significativity in the Wilcoxon test. See Sect. 2.6 for the questions details.

From the analysis of the Presence related questions (Fig. 3) it emerges that the Visuo-Haptic condition, as expected, provides a stronger sensation of passive motion. Difference in question P5 is highly significant. Similar results are obtained with the P3 question on the congruence between modalities. The strength of the Visuo-Haptic feedback emerges also from the Embodiment questions (Fig. 4): in particular E8 and E9 result significatively different between the two conditions.

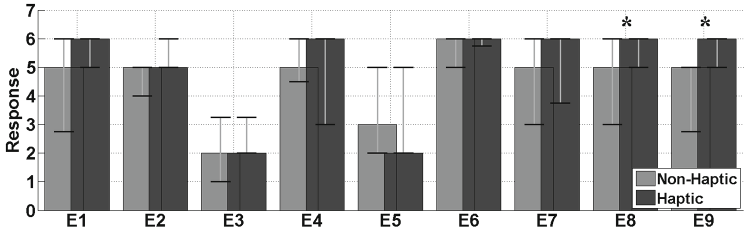


Fig. 4. Embodiment questions. Bars report the average value with error value. Asterisk means normal and high significativity in the Wilcoxon test. See Sect. 2.6 for the questions details.

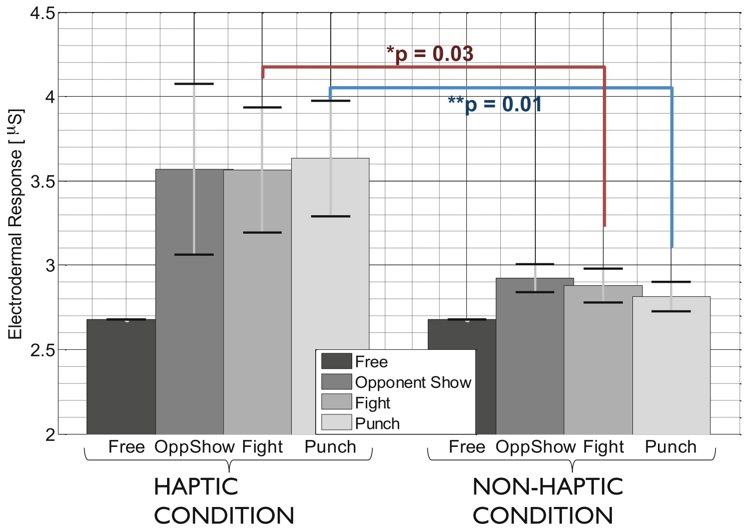


Fig. 5. Electrodermal response representing the two conditions and the four phases inside every session, compired pairwise.

These results support the physiological assessment provided by EDA that shows not only a high difference of response among corresponding sessions, but also that in the Visuo-Haptic condition the response increases in the final phase, while it decreases in the Visual condition. These results present promising possibilities in the use of combination of haptic feedback and avatars for the experimentation of perception of danger, and possibly for application of behavior transfer through virtual environments.

4 Conclusions

The experiment presented in this work, and the system described in this paper, are opening new possibilities in the experience of body ownership, combining the exploration of virtual environments with the physical interaction with avatars. The introduction of the haptic feedback increases the level of ownership and this fact can be used for exploring more complex scenarios of social interaction through virtual embodiment. The ALEx exoskeleton and the proposed Virtual Human engine provide at the same time the possibility of exploring the direction of immersive training with a new level of realism. The video illustrating the experiment and the results is shown at the following link: https://www.youtube.com/watch?v=3drtyM-mk_4.

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