Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation

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ABSTRACT
We present impacto, a device designed to render the haptic sensation of hitting and being hit in virtual reality. The key idea that allows the small and light impacto device to simulate a strong hit is that it decomposes the stimulus: it renders the tactile aspect of being hit by tapping the skin using a solenoid; it adds impulse to the hit by thrusting the user's arm backwards using electrical muscle stimulation. The device is self-contained, wireless, and small enough for wearable use, and thus leaves the user unencumbered and able to walk around freely in a virtual environment. The device is of generic shape, allowing it to also be worn on legs so as to enhance the experience of kicking, or merged into props, such as a baseball bat. We demonstrate how to assemble multiple impacto units into a simple haptic suit. Participants of our study rated impacts simulated using impacto's combination of a solenoid hit and electrical muscle stimulation as more realistic than either technique in isolation.

ACM Classification: H.5.2 [Information interfaces and presentation]: User Interfaces: Input Devices and Strategies, Interaction Styles.

Keywords: haptics; impact, virtual reality; mobile; wearable; electrical muscle stimulation; solenoid; force feedback

General terms: Design, Human factors.

INTRODUCTION
The objective of virtual reality systems is to provide an immersive and realistic experience [28]. While research in virtual reality has traditionally focused on the visual and auditory senses, many researchers argue that the next step towards immersion must include haptics, i.e., to allow users to experience the physical aspects of the world [12, 24, 32].

In this paper we focus on one specific category of haptic sensation, namely *impact*, i.e., the sensation of hitting or being hit by an object. Impact plays a key role in many sports simulations such as boxing, fencing, football, etc.

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Simulating impact is challenging though. Creating the impulse that is transferred when hit by a kilogram-scale object, such as a boxer's fist, requires getting a kilogram-scale object into motion and colliding it with the user. This requires a very heavy device. In addition, building up an impulse requires an anchor to push against (Newton's Third Law), typically resulting in a tethered device, e.g., SPIDAR [22]. Both clash with the notion that today's virtual reality hardware is already wearable and wireless [9].

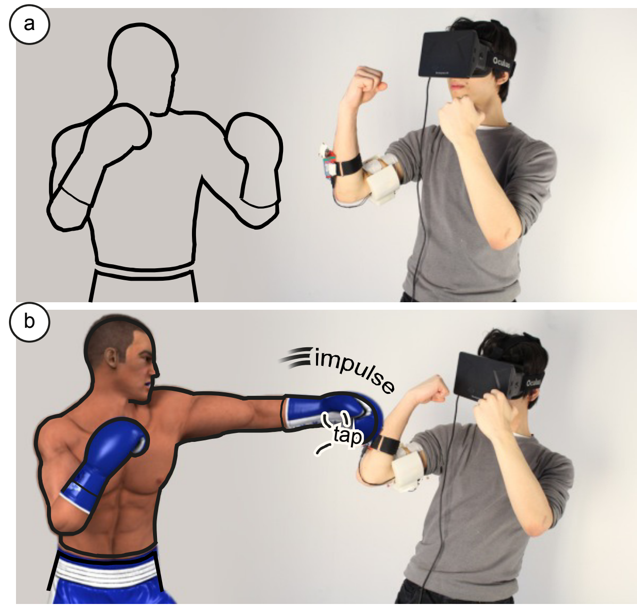

Figure 1: Impacto is designed to render the haptic sensation of hitting and being hit. The key idea that allows the small impacto device to simulate a strong hit is that it decomposes the stimulus. It renders the tactile aspect of being hit by tapping the skin using a solenoid; it adds impulse to the hit by thrusting the user's arm backwards using electrical muscle stimulation. Both technologies are small enough for wearable use.

In this paper, we propose a different approach. The key idea is to decompose the impact stimulus into two sub stimuli, each of which we can render effectively.

IMPACTO: ELECTRICAL MUSCLE & TACTILE STIMULI
Impacto is designed to render the haptic sensation of hitting or being hit. Figure 1 illustrates our approach, here at the example of a boxing simulation. The key idea that allows the small and light impacto device to simulate a strong hit is that it decomposes the stimulus. It renders the tactile aspect of being hit by tapping the skin using a solenoid; it adds impulse to the hit by thrusting the user's arm backwards using electrical muscle stimulation. Both technologies are small enough for wearable use.

Figure 2 shows the solenoid component in detail. To achieve a compact form factor, the solenoid is mounted parallel to the user's skin. A lever mechanism redirects its impact by 90 degrees, allowing it to hit the user's skin at a perpendicular angle.

Furthermore, we provide a set of exchangeable 3D printed tips to refine the desired tactile experience, e.g., to simulate boxing without gloves we use a tip that resembles human knuckles (Figure 2c). In addition to the knuckles, Figure 2 shows: (a) a generic surface, e.g., for punching a virtual avatar, (b) a small generic surface, e.g., for receiving a sharp impact, (d) a rounded surface, e.g., for jugging a ball, and (e) a sharp tip, e.g., for getting hit by a fencing weapon.

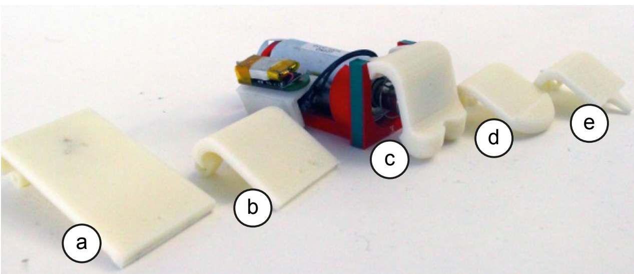

Figure 2: The solenoid component with a "knuckle" tip (c), which has a 90-degree lever to hit the skin orthogonally. The other four interchangeable tips are (a) generic surface, (b) small generic surface, (d) rounded, and (e) sharp.

Figure 3 shows the electrical muscle stimulation component. Its electrodes are mounted to the specific muscle that is able to render the impulse response that matches the solenoid. Here the solenoid is mounted to the outside of the arm, and therefore matches the impulse that would cause the arm to flex. Hence, we use the muscle that can flex the user's arm, i.e., we attach the EMS component to the user's biceps. When activated, the electrodes trigger an involuntary contraction of those muscles, simulating the transfer of impulse by thrusting the arm backwards.

Figure 3: Detail of the electrical muscle stimulation component. Here, it stimulates the user's *biceps brachii* muscles causing an involuntary contraction that resembles force feedback.

Figure 4 shows the control unit that drives both solenoid and EMS components. We built impacto as a stand-alone and wearable device, with all electronics embedded in a bracelet. The solenoid module features a Velcro closure, allowing the device to be strapped to the user's upper arm, back of the hand, the user's leg and so forth.

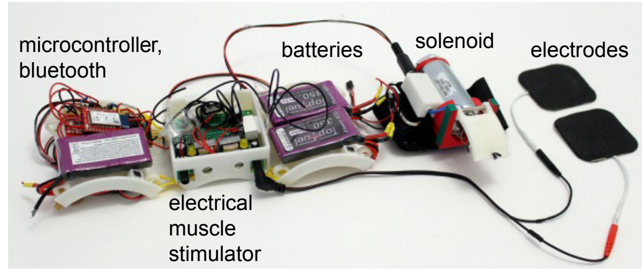

Figure 4: The Impacto bracelet opened to reveal its contents: Arduino microcontroller, bluetooth, electrical muscle stimulation, batteries, solenoid and electrodes.

Impacto's two components are mutually beneficial

Even though both technologies are small enough to allow for mobile or wearable use, it is their combination that creates a very strong sensation—in fact, stronger than either of the technologies by themselves (see "User Study"). However, solenoid and EMS play well together in more than one way:

1. Impacto simulates an impulse. The EMS component actually *moves* the arm. To create the required impulse, it creates a mechanical system between the limb and the user's torso. Given that the torso is comparably massive, there is very little effect on the torso and a strong effect on the limb.

2. The physical response produced by EMS is strong, despite the small form factor. It achieves this by leveraging the user's skeleton and muscles [21].

3. Because of the EMS, the solenoid can be small, wearable. Because the EMS is small but does the "heavy lifting", the task of the solenoid is limited to tapping the skin. This keeps the size of the solenoid down. With a small solenoid and EMS, we achieve a compelling simulation in a mobile/wearable form factor.

BENEFITS AND CONTRIBUTION

Our main contribution is the concept of impact simulation, its decomposition into tactile and impulse components, and the implementation of these two components using solenoid and electrical muscle stimulation. The main benefit of our approach is that it makes the simulation of a strong impact feasible in a small form factor. Our user study suggests that our approach generates a stronger sensation than either component in isolation. We demonstrate the use of our device in a series of virtual reality sport simulators.

On the flipside, simulating multiple impact locations requires multiple units, which places a natural limit on the spatial resolution of the simulation. Also, using a solenoid as a tactile feedback source adds inherent latency, which needs to be compensated for. Lastly, the use of EMS requires electrodes, which need to be manually placed by the user and calibrated prior to use.

APPLICATION EXAMPLES

We have implemented three virtual reality sport simulators to demonstrate the potential use of impacto. All our examples use impacto for haptic feedback, an Oculus Rift for visuals and a Kinect for tracking. We now describe the applications from the perspective of what the user feels.

Hitting and being hit—Boxing

Boxing is a sport for which the notion of impact is crucial. Figure 5 shows a screenshot of the simple boxing simulator we created to experiment with impacto. In this simulator, users can fight a virtual avatar by boxing. The avatar keeps its guard up and attacks periodically. Users must choose the right moment to unleash a successful attack. It takes ten successful hits to take down the avatar, which causes a new opponent to appear and the simulation continues.

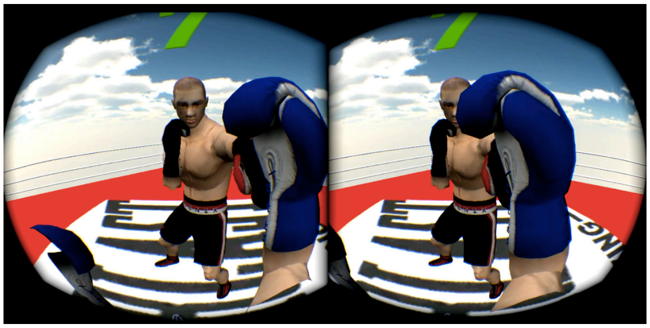

Figure 5: Stereo headset view from our simple boxing simulation. It allows users to attack the avatar and to block the avatar's attacks. Here, we see the avatar attacking the user's right arm.

Figure 6 illustrates how impacto adds a haptic component to the simulation: (a) The simulator provides haptic feedback when the user blocks the avatar, as discussed earlier. (b) The same impacto unit allows the user to hit the avatar using the part of the arm that wears the impacto unit, here the back of the arm.

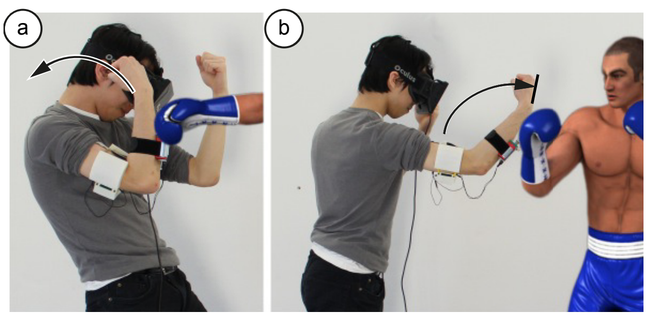

Figure 6: (a) Impacto allows users to feel the impact of blocking the avatar's hit by thrusting the user's arm backwards by operating the user's biceps. (b) The same impacto unit allows simulating the sensation of attacking. In both cases the impacto unit activates the user's biceps. This time, this causes the user's hand to stop in mid-air, as if it had hit the opponent.

Attacking using the back of the arm is an unusual (even illegal) attack in boxing. To allow the user to attack using other parts of the arm and/or to allow the avatar to attack additional targets on the user, we use additional impacto units. In the setup shown in Figure 7, we mounted a second solenoid component to simulate impact on the user's fist. This allows the user to attack using jabs and uppercuts. Since a knuckle hit leads to a similar impulse as the back of arm attack and block, we let both solenoid components share the EMS components on the user's biceps.

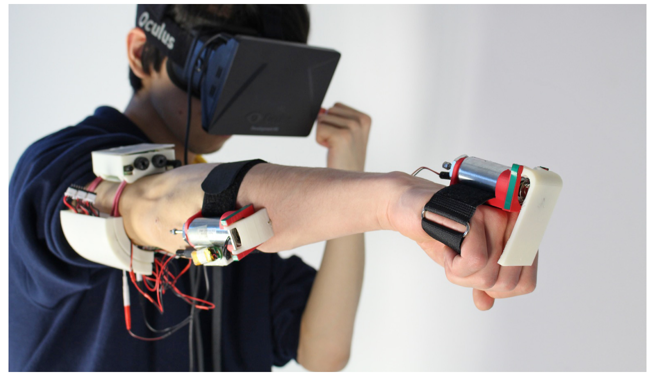

Figure 7: Additional solenoid unit mounted to the back of the hand featuring a surface tip allows the user to attack using jabs and uppercuts.

Applying impacto to other limbs—Soccer

Impacto units can be used on other limbs and muscles, such as the triceps, quads, etc. In Figure 8 we mounted a unit to the user's calves.

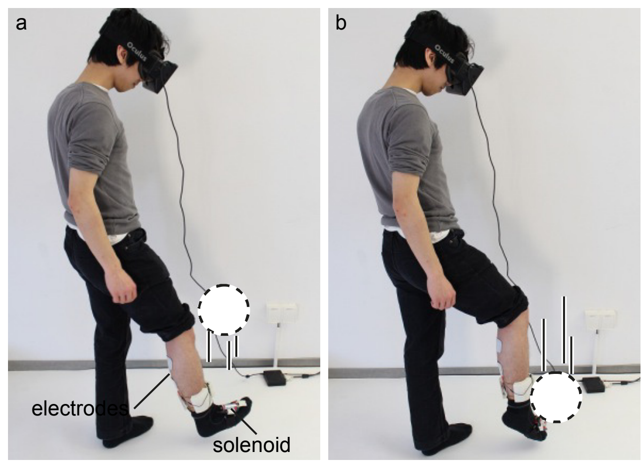

Figure 8: By wearing impacto on the leg and foot, the user experiences the impact of kicking a virtual football.

Figure 9 shows the simple simulator we implemented to illustrate this use case. It allows users to juggle a virtual soccer ball.

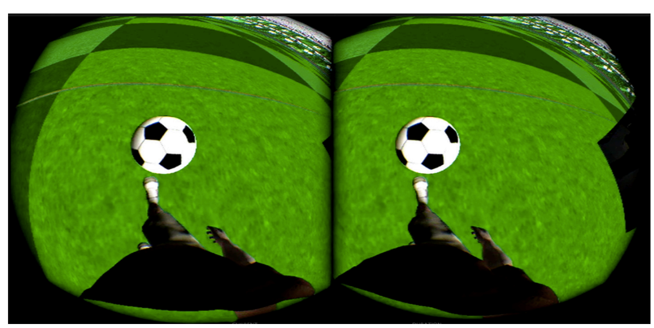

Figure 9: Stereo headset view from the football-juggling simulator. Here, the impacto unit renders the impact of a ball on the user's foot.

This setup points the solenoid component at the user's instep (top of the foot) and the EMS unit to the calf muscles (*gastrocnemius*), as depicted in Figure 10. We operate the unit so as to slightly push the foot backwards at the moment the ball hits the foot.

This football-juggling simulator uses the same Kinect setup as the boxing simulator. Additionally, to obtain the foot's tilt angle, we mounted a wireless accelerometer to the solenoid component.

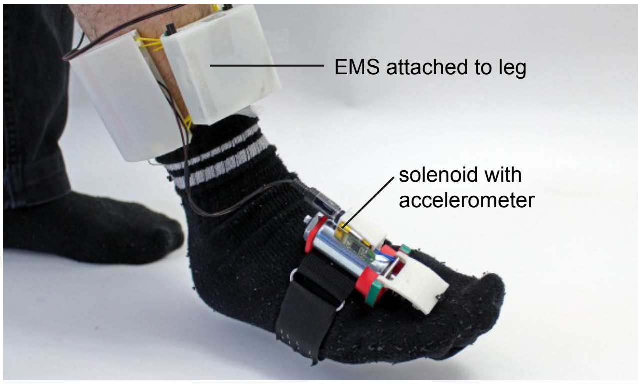

Figure 10: Close-up of on impacto unit mounted on the user's instep and calf. The wireless accelerometer on the solenoid senses the foot's tilt.

Combining impacto units—Thai Boxing

Users can experience impact sensations spread across multiple locations of their body by wearing multiple units. In Figure 11, we combined the setups from the boxing and the football-juggling simulator, resulting in a simple Thai boxing simulator.

Figure 11: Combining impacto units on arms and legs allows us to support a simple Thai Boxing experience.

Feeling Impact on Props—Baseball

The decomposition of impulse and tactile sensation transfers readily to hand-held props. Figure 12 illustrates this at the example of a simple baseball simulator.

In the baseball simulator, by wearing an impacto unit, the user experiences the impact of an incoming baseball against the bat (Figure 13). To enable the prop, here a stand-in for a baseball bat, we mount the solenoid onto the prop; the EMS unit, in contrast, stays with the user and stimulates the wrist extension muscle (*extensor digitorium)*.

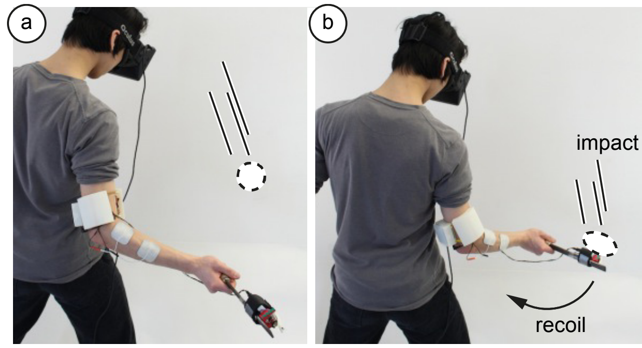

Figure 12: User hitting a virtual baseball. The impacto unit renders the impact of the ball by tapping the solenoid onto the prop and slightly extending the wrist backwards using the EMS component.

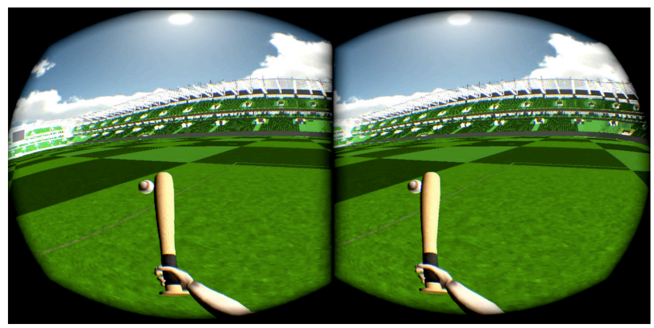

Figure 13: Stereo headset view from our simple baseball simulator. Here, the impacto unit renders the impact of the baseball hitting the bat, which in reality is a mere prop.

As illustrated by Figure 14, the same prop and electrode placement can power additional applications: by replacing the visuals in the virtual world and adjusting impacto's response, we can reuse the same prop to simulate a baseball bat, a fencing weapon, or a ping-pong paddle

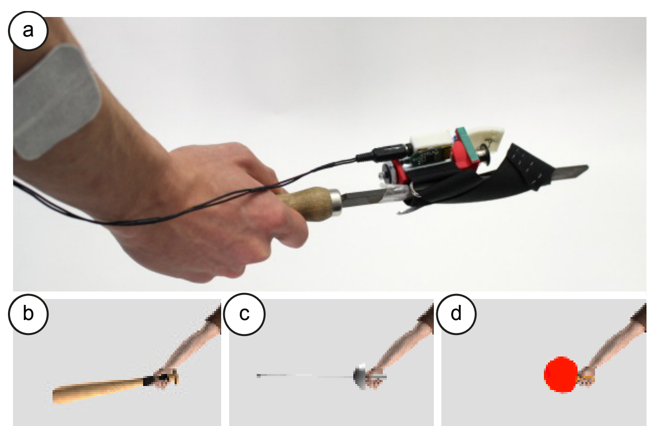

Figure 14: (a) Adjusting impacto's response and updating visuals turns the same prop into a range of different experiences, such as (b) a baseball bat, (c) a fencing weapon or (d) a ping-pong paddle.

RELATED WORK

The work presented in this paper builds on tactile stimulation, force feedback, virtual reality, and electrical muscle stimulation.

Tactile Stimulation

Tapping on the user's skin was, for example, used by Li et al. in order to convey messages [19]. Tapping is a special case of tactile feedback and it generally leads to a better tactile sensation than vibrotactile actuation because the tapping stimulates the SA1 receptors (Merkel cells) that sense pressure. Vibrotactile feedback, in contrast, is only sensed by the Pacinian corpuscles, which do not contribute to pressure sensing [18].

A common approach to recreate tapping is to emulate it using vibration. Lindeman et al. simulate impact in virtual reality using a suit that contains vibrotactile actuators [9]. In their virtual reality shooting application the suit communicates the spatial location of shots by activating the respective vibrotactile cell. However, there is no net force, thus no displacement of the user's limbs.

Furthermore, tactile stimuli have also been transmitted through the air around the user using ultrasonic waves [14] or air vortexes [27]. These approaches require the emitters to be positioned in front of the user, are prone to occlusion and restrict the interactive space to a meter.

Force feedback

Impacto's way of simulating the transfer of impulse is a special case of force feedback.

Force feedback systems attach to the users' limbs using exoskeletons, such as the *Utah Dextrous Hand Master* [13] or the *FlexTensor* [31], or pulley systems, such as *SPIDAR* [22]. Mechanical force feedback actuators of this kind tend to use an external apparatus mounted on the user, such as pulleys or an exoskeleton.

Variations of the SPIDAR design have been used in CAVE-like simulators with force feedback, in particular a boxing simulator [11] and a catch-ball simulator [15].

Another approach is to use a robotic arm for force feedback, such as in the system by Yokokohji et al. [33]. Similarly, Gruenbaum et al. leverage an industrial robotic manipulator as a stand-in for a control panel of a virtual automobile [10].

Furthermore, approaches based on pseudo-force feedback, such as Traxion [26], create the illusion of a small force (up to 0.292 N). The effect is accomplished using asymmetric vibrotactile stimulation.

Force feedback using electrical muscle stimulation

More recently, researchers started administering force feedback using electrical muscle stimulation (EMS) to achieve force feedback in a compact form factor (e.g., Muscle Propelled Force Feedback [21]).

Farbiz et al. used EMS on the wrist muscles to render the sensation of a ball hitting a racket in an augmented reality tennis game [7]. However, this system does not create a tactile component that supports the impact experience.

Transmitting impact through handheld props

In the 1970's baseball game arcade, Trzesniewski attached a solenoid to the bat to render the impact feedback [30]. Similarly, Teck et al. simulate the impact of a virtual ball on a tennis racquet by attaching a solenoid to the prop [29]. They found that the output force generated by the high-power solenoid is two orders of magnitude below the force of a real ball hitting the prop [29]. This is why impacto is inspired by such approaches, but, additionally, uses EMS to render the strong force feedback sensation.

Combining force feedback and vibration

The haptic glove by Kron et al. is essentially a force feedback hand exoskeleton with an eccentric motor on each finger [17]. During use, vibrations signal contact with a virtual object. The concept of haptic gloves goes back as far as 1987's Data Glove by VPL [8]. Another example of a haptic glove with vibration is the Cyber Glove Force by Kramer et al. [16]. These combined systems are promising, however, vibrating the skin does not elicit the same sensory receptor as actually tapping the skin [18].

IMPLEMENTATION DETAILS

To help readers replicate our design, we now provide the necessary technical details.

Impacto's Hardware

Figure 15 shows the circuitry inside the impacto bracelet. The bracelet uses three 7.4 V LiPo cells in series for a total of 22.2 V and 1050 mAh to drive the solenoid in the boxing simulation; for simulations that involve weaker impacts, such as football, we used half the voltage. The estimated power consuption is: EMS (0.1 A), solenoid (0.5 A~0.7 A) and microntroller & bluetooth (0.2 A), allowing the unit to run for ~2000 hits.

The Arduino Pro Micro microcontroller (3.3 V, 8 Mhz) receives commands from the virtual reality applications via a bluetooth module (RN42XVP).

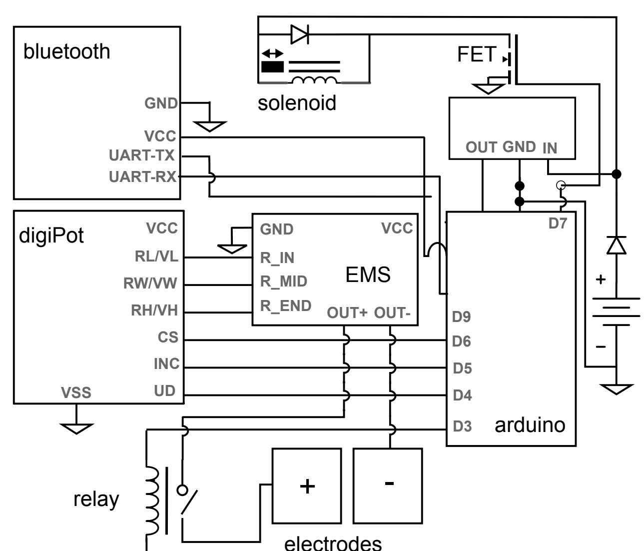

Figure 15: Schematic of impacto's circuitry.

The microcontroller and EMS unit (TrueTens V3) are powered through a 9 V voltage regulator (LM7809). The solenoid receives power directly from the battery (22.2 V). Optionally, the solenoid power can be regulated down to 20 V via another adjustable voltage regulator (LM317).

The unit can control EMS and solenoid intensity separately. One non-volatile digital potentiometer (X9C103) controls the intensity of the electrical muscle stimulation; the microcontroller controls it via a 3-wire protocol. One relay (HFD4/3) switches the EMS channel on/off in 3 ms.

An N-Channel MOSFET (BUZ11) controls the intensity of the solenoid. It is sensitive enough to trigger at the low current output from the ATMEGA and can switch 30 A, which lies comfortably below the drain of our solenoid. The solenoid is bridged with a N4007 flyback diode to prevent the microcontroller from resetting due to the electromotive force that builds up when the solenoid is switched off. Modules that feature two solenoid outputs can switch between them using an additional relay (ommited from schematic).

The 3-axis wireless accelerometer in the football juggling application is an Axivity WAX3; it sends data wirelessly to the computer running the simulations. We pass the accelerometer data to the applications using the Axivity Wax library [1] via serial. The accelerometer's internal battery allows the device to run for 8 hours.

Modular Design

Our design allows users to re-arrange the modules when transitioning to a different VR scenario, such as from a boxing simulator to a football simulator. Figure 16 depicts the four steps to attach impacto to the arm.

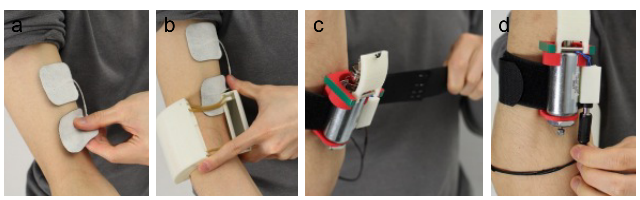

Figure 16: (a-d) Impacto allows switching between experiences by rearranging components. (b-c) Wearable form-factor and Velcro closures make this fast. Here, we see a user attaching impacto to the arm.

VR Simulators and Tracking

We implemented all sports simulators in Unity 3D. All our applications use a Kinect to track the user's skeleton; it is connected to Unity 3D via the Microsoft's Kinect SDK Wrapper. The Unity3D system detects collisions using collider objects attached to the skeleton of the user as represented in the virtual world. When a collision is detected, the system sends a serial message over bluetooth to the impacto unit attached to that limb (each unit has its own bluetooth address). The message contains which EMS channel and solenoid to trigger as well as the desired intensity. Users experienced all applications through an Oculus V1 head mounted display.

The solenoid mechanics and wireless communication are inherently subject to 60 ms of lag. One way to make the system appear instantly responsive is to have Unity3D using colliders with bounding volumes 25% larger than the actual limb, causing the collider to trigger ~30 ms early, thereby compensating for the lag of the system. On the flipside, this technique does not work for targets spatially clustered together or if the user stops abruptly before the target, as it creates a false positive.

Measuring latency

We determined the device's lag using a series of measurements on the apparatus depicted in Figure 17. This apparatus drives impacto's solenoid, making it tap a load-cell (MSP6951-ND) sampled at 1 kHz by an ATMEGA328 microcontroller, and measures the time difference.

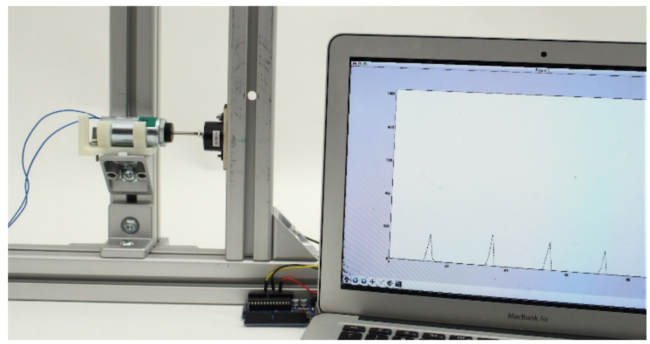

Figure 17: Apparatus for measuring force and latency.

As a baseline we compare latency over bluetooth to direct serial connection, i.e., tethered over USB. Using a high-speed camera we measured 11 ms for the microcontroller to receive a single byte over USB and to turn on an LED in response. The HFD4/3 relays take a maximum of 3ms to actuate (from datasheet). Using our apparatus, we measured that the solenoid takes 10~20 ms to extend fully and hit the load cell. Finally, our apparatus measured a latency of 50~60 ms for a tactile hit (bluetooth + solenoid mechanics), which lies within the haptic threshold of 50-200 ms, as set by psychophysics research [25].

Impacto's hardware limitations

The current setup is based on a Kinect for tracking and bluetooth for communication, which account for most of the latency; future versions of impacto will use lower latency trackers such as accelerometers and communicate over bluetooth 4.0 at faster baud rates, which is substantially faster than our current implementation.

Furthermore, as any system based on surface electrical muscle stimulation, Impacto requires the correct placement of the electrodes onto the user's skin. This procedure requires an understanding of where the muscles are located and takes about 10-30s for the biceps for a trained user. The current version of impacto does not provide a closed loop measurement of the user's skin resistance. Thus, any change in skin resistance will affect the intensity of the force feedback effect. In fact, state of the art EMS systems are starting to feature a closed loop sensing with galvanic reading of the user's skin resistance [6].

Measuring loss at the 90° lever

To validate the mechanical design, in particular the deflection lever, which pulls the tip using a fishing string, we conducted a series of force measurements. The deflection lever redirects the solenoid's impulse by 90°, allowing the solenoid to be mounted parallel to the user's skin providing a much more compact form factor. We reused the apparatus shown in Figure 17 in two conditions, i.e., with and without the deflection lever.

Our measurements show that force exerted by the vertical hit (as in "User Study") is 26 N, while for the horizontally mounted solenoid, which hits through the 90° lever, we measured 21.1 N. Measurements are an average of 10 hits on the load-cell using the knuckle tip. These measurements clarify that both setups are comparable.

USER STUDY

To validate the core idea behind impacto, i.e., the idea of decomposing an impact's haptic feedback into a tactile component (*solenoid*) and an impulse component (*EMS*), we conducted a user study. To do so, we immersed participants in a simplified study version of our boxing simulator in which they blocked punches by an avatar opponent. We varied the intensity of *solenoid* (no, low, high) and *EMS* (no, low, high) in a full-factorial design and asked participants to assess the realism of the punches. We hypothesized that the combination of both stimuli would lead to a more realistic experience.

Apparatus

Figure 18a shows our apparatus. Participants wore a head-mounted display (Oculus Rift V1). A single impacto unit was mounted to their right forearm, with the electrodes of the EMS component attached to the participant's *biceps brachii* muscle. We used an earlier design of impacto, however, it used the same EMS component and produced similar output force conditions as the bracelet (see previous section). For the tactile sensation we used the knuckle tip.

To ensure a controlled experience, we used a scripted version of our boxing simulation, in which a video avatar repeatedly punched the participant (Figure 18b) on the dorsal side of their right forearm.

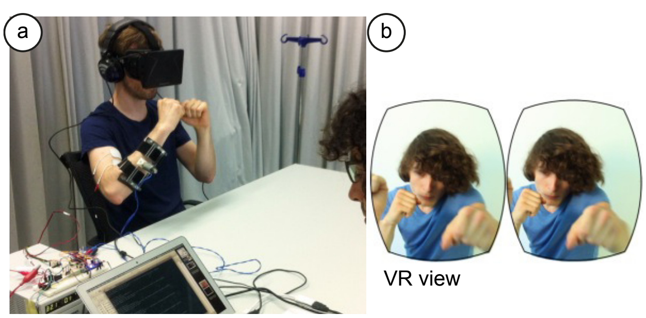

Figure 18: Experiment setup: (a) Participant wearing the head mounted display, electrodes on the biceps and the impact module on the right forearm. (b) The visual stimuli participants received through the head mounted display showed a first-person-view of a boxing experience.

Participants were seated and held their arms in a guard position, so as to match the hands they saw in the video experience. Participants rested their elbows on the table between trials to reduce fatigue.

Interface conditions

There were nine interface conditions, i.e., the full-factorial design of *solenoid* intensity (*no, low, high*) and *EMS* intensity (*no, low, high*).

In the *high EMS* conditions, the EMS component was calibrated to perform a full biceps curl, i.e., a 45 degrees movement from the default guard pose. In the *low EMS* conditions, the EMS component was calibrated so as to create the weakest visible contraction of the participant's biceps. In the *no EMS* conditions, the EMS component was off.

During setup, we made sure that participants felt conformable with the setup and reached 45 degrees without any discomfort. This was the case for all participants.

In the *high solenoid* condition we overdrove the 12 V solenoid with 32 V for 200ms, resulting in a strong (~26 N) tap. In the *low solenoid* condition we operated the solenoid at its nominal voltage of 12 V for 200 ms resulting in a weaker (~13 N) tap. In the *no solenoid* condition, the solenoid remained off.

Task and Procedure

For each trial, participants observed a 9 seconds video experience of being punched against their guard 3 times. This was accompanied by the respective haptic feedback created using the impacto unit. Participants then rated the realism of the punches on a 7-point Likert scale (1 = artificial, did not feel like being punched, 7 = realistic, like being punched).

Each participant performed a total of 27 trials: 3 force feedback settings (*no EMS, low,* or *high EM*S strength setting) × 3 tactile feedback settings (*no solenoid, low*, or *high*) × 3 repetitions. This yields a 3 × 3 within-subjects design.

The EMS calibration procedure took about 4 minutes during which the biceps contraction was repeated ten times to ensure that a similar contraction was found.

Participants

We recruited 12 participants (3 female), between 22 and 35 years old (*M* = 26.9 years) from a nearby organization. We excluded a thirteenth participant from the analysis who had stated that he/she had started with too high ratings, thereby producing a ceiling effect. One of the participants had boxing experience (sparring) and another was trained in martial arts. Two participants had never experienced a VR headset before and only one had experienced EMS before (in physiotherapy). With consent of the participants we videotaped the study sessions.

Results

Figure 19 shows the resulting data, i.e. participants' assessment of the realism of the punches as a result of the different haptic feedback conditions. We analyzed the data using a 3 *(EMS)* × 3 *(solenoid)* × 3 *(repetition)* repeated measures ANOVA (α = .05) as suggested by [23]. Since we found no learning effect as there was no main effect of repetition ($F_{2,25}$ = 0.225, p = .800), we used all three repetitions as data.

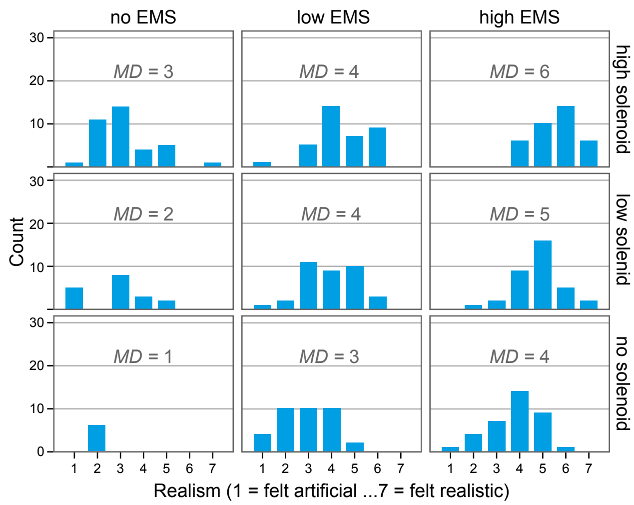

Figure 19: Realism ratings in dependence of force feedback (*EMS*) and tactile feedback (*solenoid*) conditions.

As expected, we found main effects for force feedback (*EMS*, $F_{2,14}$ = 89.726, p = .000) and tactile feedback (*solenoid*, $F_{2,14}$ = 56.840, p = .000, Greenhouse-Geisser corrected for sphericity), i.e., *higher solenoid* intensity and *higher EMS* intensity both led to more realism. We did not find any interaction effect of *EMS * solenoid* ($F_{2,14}$ = 1.524, p = .210).

Post hoc pair-wise comparisons using the test (Bonferroni corrected) confirmed the statistical differences across intensity levels for both, *EMS* (all pairwise comparisons, $p < .001$) and *solenoid* (all pairwise comparisons, $p < .001$).

Participants' feedback after the experience

After finishing all trials we interviewed participants about their experience.

Seven participants stated that they found the experience "immersive". Referring to the first time he/she had felt the combined effect P4 stated "it got immersive after a while, when I felt a stronger hit for the first time". P7 said "the first time I felt it, it was surprising, felt like a realistic force". P4 also added "I felt I needed to protect myself from the hits, it got real for me". P10 went further and stated: "this seems to really help VR, it is the most realistic VR experience I've ever had". P3, who was acquainted with boxing/sparring, stated "I know the feeling [impact] from sparing and this was really cool, could be even stronger [the solenoid hit]" and added "it is really impressive that this actually moves my arm".

All participants stated that they liked the combined effect better than the individual effects, as suggested by their earlier assessments of "realism", P5 explained "the stimulation does not feel like a hit, but the combination really feels real because I suppose if you get hit your muscle moves back after the skin is hit". P8 said "I clearly felt that a hit [solenoid] and response [EMS] made it much more real". P7: "The solenoid feels like a punch and so its more important but then only with the EMS it felt real". Similarly, P9, who had 10 years of martial arts experience, said "solenoid is more important because it is like getting hit, but I prefer when both are on." P10 said "The EMS helps, but the primary thing is that it touched me." P12: "if you have solenoid, then the EMS really helps me to feel [that it is] real". P2 said "I was skeptical of the EMS during the calibration, but when I saw it in combination with the VR video and the solenoid, it was impressive".

Four participants stated that without the solenoid the experience feels unrealistic, such as "without the solenoid it was hard to understand when [the virtual boxer] hit me" (P3).

Three participants pointed out that the EMS tingling had slightly affected their sense of realism "I felt it vibrating, so that is a bit different from the pure movement" (P4).

When asked "what is missing for a fully realistic experience" participants answered: "resolution of the headset" (P10, P8), "remove the tingling caused by the EMS" (P12, P13), "it should also actuate my shoulder" (P4), and "the tactile part should be a larger surface, like a fist model" (P11, P9).

Discussion

Our study found main effects on both EMS and solenoid, suggesting that increasing the intensity of either of the haptic effects increases the perceived realism. The highest score, however, was achieved by combining both stimuli, supporting our hypothesis. Participants' comments further support that hypothesis in that *all* participants stated that the combined effect had felt more realistic than either individual effects.

CONCLUSIONS

We introduced Impacto, a wearable device that allows users to experience impact in virtual reality. The key idea that allows the small and light impacto device to simulate a strong hit is that it decomposes the stimulus. It renders the tactile aspect of being hit by tapping the skin using a solenoid; it adds impulse to the hit by thrusting the user's arm backwards using electrical muscle stimulation. Both technologies are small enough for wearable use. We demonstrated a proof-of-concept module in three VR applications, each demonstrating that impacto enables a variety of haptic sensations, such as being hit or hitting back, by directly attaching it onto the user's body or even mediated through a passive prop.

As future work, and to increase the fidelity of the force feedback, we plan to apply impacto to other locations such as the abdominal muscles or shoulders, as to generate a larger output motion.

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