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UNTETHERED FORCE FEEDBACK FOR VIRTUAL AND AUGMENTED REALITY INTERACTIONS

ECSE 457 - DESIGN PROJECT

DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

Group 2

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ABSTRACT

The goal of this project is to design a wearable and mobile system that is to be integrated in a virtual or augmented reality environment to provide force feedback to the user. The system needs to be lightweight and compact to allow freedom of movement for the user. The benefits of this research are primarily related to increasing the realism of interactions in VR environments, with application possibilities to entertainment, gaming, and training simulations involving use of tools, e.g., in surgical procedures. The project focuses on two parts of the body - hands and arms. Because of their difference in morphology and operation, arms and hands require two separate force feedback systems, better adapted to their respective characteristics. The scope of the project includes researching, designing, assembling, and testing. This semester, the team has finished assembling a prototype of the full system with the hand exoskeleton (actuation of two finger only) and arm EMS linked to a virtual environment which contains a playable scenario. Some preliminary testing has also been completed.

ACKNOWLEDGMENTS

We wish to thank Donald Pavlasek for the time he spent with our team and his precious mechanical expertise that helped us moving forward with the exoskeleton design. We also thank Jeff Blum and Pascal Fortin for their valuable technical expertise and support on this project. Thank you to Pedro Lopes for his valuable guidance in the designs of the EMS and exoskeleton systems. Finally, we would like to thank our advisor, Prof. Jeremy Cooperstock for his time, assistance and advice during the past two semesters.

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LIST OF ABBREVIATIONS

3D	-	3 Dimensional
ABS	-	Acrylonitrile Butadiene Styrene
AR	-	Augmented Reality
CAD	-	Computer-Aided Design
CAD	-	Canadian Dollars (if preceded by a dollar sign)
CO2	-	Carbon Dioxide
EMS	-	Electro-Muscular Stimulation
FPS	-	Frames Per Second
GPU	-	Graphics Processing Unit
HMD	-	Head Mounted Display
HTC	-	High Tech Computer Corporation
IR	-	Infrared Radiation
LED	-	Light-Emitting Diode
MoCap	-	Motion Capture
MOSFET	-	Metal-Oxide Semiconductor Field-Effect Transistor
PLA	-	Polylactic Acid
PVA	-	Polyvinyl Alcohol
USB	-	Universal Serial Bus
VR	-	Virtual Reality

INTRODUCTION

Virtual Reality is the concept of implementing a virtual environment in which a user receives convincing sensitive feedback that tricks him/her into thinking that the virtual experience is real. VR industries aim to constantly improve the visual, audio, tactile, and space tracking technologies to create more immersive experiences. Their technologies can positively impact society in many ways. For example, a study shows that haptic feedback implemented in surgical simulations improved the performance of students in the real world and accelerated their training [1]. VR can also provide new sources of entertainment, like the HTC Vive, which is a VR system used in gaming. Gaming is a way to escape from stress and provides a different world that one can enjoy in ways that are not possible in the real world. The increased immersion the HTC Vive makes this escape more effective.

Current commercialized technologies in VR only produce very limited levels of haptic feedback. Products such as the HTC Vive or Oculus Rift use vibration motors but these do not effectively apply force feedback – the user does not receive a strong, realistic resistance acting against his hands coming from a specific direction. Other solutions that provide more realistic force feedback lack mobility. For example, the Sensable Phantom offers resistive feedback by utilizing a reverse robotic arm mechanism that provides the user with the feeling of touching an object in virtual space [2]. However, its current grounded design prevents mobility.

The most necessary sense to live a normal life is the sense of touch. It provides the most feedback information required to coordinate the body and creates the sense of "knowing" where your body is situated in space [3]. Without it, you would feel lost in the physical world. Thus, it is important for a VR system to convincingly stimulate the user's sense of touch as he/she experiences the VR environment. Force feedback – the ability for the user to feel physical resistance applied against his/her body - plays a tremendous role in achieving this level of tactile immersion. It is also key that the system allows for user mobility: it increases the sensation of touch through the force from the ground to the legs, and so increases the sensation of "knowing". More importantly, mobility allows for many more applications - those that can require freedom of movement of the entire body. For example, VR can be used as a physical rehabilitation tool. It allows to bring “the complexity of the physical world into the controlled environment of the laboratory” [4], also providing real-time performance feedback in a safe testing and training environment [4]. In this case, a compact and lightweight system can allow for the rehabilitation of almost any body parts.

The goal of the project is to design a mobile system that applies convincing force feedback on a user in a virtual environment. The team decided to focus in particular on force feedback applied on the hands and arms - they are the parts of the body that humans use the most to receive physical details about objects through touch.

BACKGROUND

Tracking:

To be able to test the hardware, feedback on the user's hand and arm positions are required to be able to apply the force feedback. Since the hardware was designed with simplicity and lightweight in mind, it currently does not provide any sensor feedback. Therefore, external tracking is needed to follow the user's movements.

Leap Motion:

The Leap Motion is a small device capable of tracking hand and finger movements. It uses three IR LEDs to display dots and two IR cameras to locate the reflected surfaces. With this information, the device can detect the hand's position in a 3D space and reconstruct it on its software. The Leap Motion can easily be integrated in game engines such as Unity3D. Due to its compact form, it makes it easy to integrate it in any situation. However, the device can only track hand positions.

Depth Cameras:

In a similar way to the Leap Motion, depth cameras projects IR dots with a powerful IR projector. A stereo IR camera retrieves the location of these dots and can reconstructs a 3D mapping of the environment. The depth can be determined by the distance between two dots: the closer they are to each other, the closer the reflected surface is. Furthermore, the dots' patterns are disrupted when the depth changes. By fitting a human skeleton to the 3D map, body position can be tracked accurately with low latency. Unfortunately, this technology is constrained by the density of the IR dots and makes finger or even hand tracking difficult.

Motion Capture:

Motion Capture is the industry standard for capturing body movement. An array of cameras is placed around the tracking area to minimize obstruction. The cameras are equipped with IR LEDs and an IR camera and are solely tracking positions of small markers. The latter are made with a special IR reflective material allowing the cameras to see them. With the proprietary software, coordinates of each markers are being tracked. Furthermore, an object's displacement and rotation can be tracked by attaching at least three markers. With very low latency and high precision, it is usually the primary tool used for tracking in research labs. However, the camera placements must be fixed after calibration to maintain high fidelity tracking and hence making the system not portable.

Computer Vision Pose Estimation:

The Computer Vision Pose Estimation algorithm [5] is the cheapest and most portable method for body tracking. It solely uses a camera to find the position of any individual in the frame. Since the hardware cannot perceive depth, it uses machine learning algorithms to plot a stickman skeleton onto the subjects. Moreover, the algorithm requires a powerful GPU to be able to computer and run the program at a stable frame rate (around 30 FPS with a Titan [6]).

Arm Anatomy:

To be able to extend the elbow (straightening of the arm) using electric stimulations, our team had to investigate the human arm anatomy to determine which muscles should be targeted. Two different muscles are involved in the extension of the elbow: the triceps brachii and the anconeus muscle. The anconeus muscle is known to add a very negligible assistance to the arm extension [7], therefore, we concentrated our efforts on targeting the triceps muscle. As shown by the picture on the right, the triceps brachii muscles run along the back of the human upper arm, from the elbow to the shoulder.

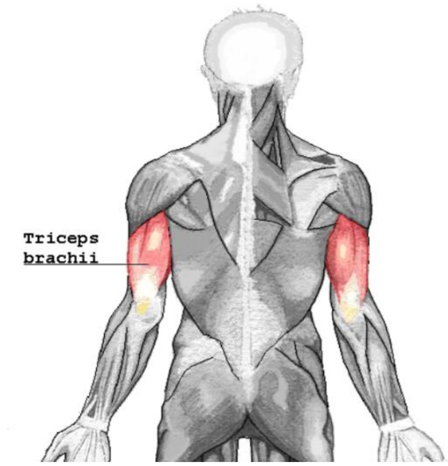


Figure 1: Arm Anatomy

The triceps and biceps muscles form an antagonist pair. A pair of muscles is called "antagonist" when it is composed of muscles that produce an opposing joint torque. Indeed, the triceps is responsible for an arm extension while the biceps is responsible for the arm flexion. The role of these two muscles (triceps and biceps) is essential for our test scenario that involves simulating the weight of an object.

PROBLEM AND REQUIREMENTS

Current force feedback systems for VR on the market have many drawbacks:

- Some are tethered (grounded), like the Senseable Phantom, which limits the types of user interactions due to lack of mobility.
- Some are bulky, which again cuts down on the amount of possible applications of the system that require user movement. It also means that there is unwanted stress applied on the user.
- Most focus on a specific body part only.
    - The exoskeletal glove designs, such as the Dexmo Glove, only apply force feedback on the hands.
    - Some designs involve EMS which can only be used to manipulate big muscles such as those in the arms or legs.
- Cost: even though The Dexmo Glove is lightweight, compact and much more discreet than many other similar designs on the market, it comes with a high price of around 12,000 CAD [8].

The team thus aims to provide a design that is wearable, compact, lightweight, applies FF on multiple areas of the body, and comes with a reasonable cost (we estimate our budget to be around 300 CAD).

There is no specific requirement for the FF system to be applied to an area of the body. It was decided that the team would focus on the user’s hands and arms as these are the parts of the body used the most to touch and sense objects around him/her. The design should not be limited to one application like a specific game or simulation. It should be able to adapt to different types of VR and AR environments used for different purposes.

DESIGN PART 1 – EMS

Placement investigation

Our team first began the EMS research by studying the arm anatomy and the different muscles playing a role when an arm extension is performed (more details on that are provided in the background section). We chose to focus on the triceps muscles as they are the ones responsible for the arm extension motion. To provide a downward force feedback, and therefore simulate the effect of gravity when lifting an object, the EMS electrodes were placed on the triceps. In order to stay in control once the EMS is actuating the triceps, the user will counter the extension by contracting the biceps and therefore, will feel like he or she is lifting a weight.

Our team investigated different electrodes placements to see which one provides the larger range of actuation and the stronger contraction. Moreover, the placement must also be comfortable, knowing that some targeted locations provide an unpleasant electric feeling or a disturbing muscle vibration.

Figure 2, 3 & 4: EMS placement

The first picture to the left illustrates the lower triceps placement. It is the easiest to target and thus, the fastest to set up. However, it only provides a force feedback when the arm is between a full extension and a 90 degrees angle, after which the electrodes fail to contract the muscle and provide and downward force.

The second picture shows the upper triceps placement. This placement requires a very precise electrode location for the muscle to be contracted. If the electrode is not perfectly place, the triceps can cramp or vibrate. However, the range of actuation is slightly improved compared to the lower triceps placement and thus provides a wider range of rotation for the elbow.

Finally, a third placement was tested, consisting of using two channels (shown in the right-most picture). The area covered by the electrodes is larger than the two previous placements and thus requires less precision when placing the electrodes. The range of actuation is similar to the upper triceps placement. However, the main drawback is an unpleasant electric current that flows and can be felt all the way down to the fingers.

For testing purposes, our team decided to sacrifice the actuation range of the EMS for a more comfortable and a placement that is easier to set up. Therefore, all the testing on test subjects was done using a lower triceps placement.

Control kit:

The EMS control kit is connected between the signal generator and the electrodes to allow an external application to scale down the signal intensity and modify the shape of the signal. MOSFets are placed in parallel with the electrodes and thus act as a current divider with the electrodes. A high MOSFet resistance causes more current through the electrodes and therefore a higher intensity of the felt signal. On the contrary, reducing the MOSFet resistance will decrease the signal intensity felt by the user [9].

Calibration:

Before every testing, the EMS sub-system is isolated from the rest of the system. The electrodes are placed on the test subject and the intensity of the generator is gently increased until a contraction is felt. This calibration phase allows the EMS signal intensity and the electrode placement to be verified and adjusted before the experiment. A wrong intensity calibration can lead to a painful sensation if the value is too high. On the contrary, the muscle will not be actuated at all if the intensity is too low. Concerning the electrode placement, a wrong position of the electrodes can lead to muscle cramps or the absence of actuation. Therefore, this calibration phase is extremely important as the results and feedback we get from the test could be distorted.

DESIGN PART 2 – EXOSKELETON DESIGN

Figure 5, 6 & 7: Hand Exoskeleton

Hand mount

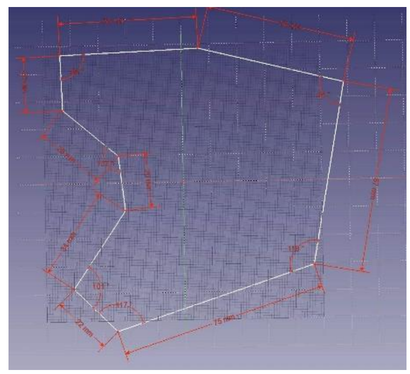


Figure 8: Hand Mount Sketch

Requirements: comfortable, thin, large enough to accommodate servo motors and knuckle rotation mechanism.
The hand mount was CADed in such a way that, the result of the 3D printing would be flexible. Doing so allowed us to mold the mount to the shape of someone's hand. When the part was properly bent so that the shape could comfortably fit our hands, the part was stuffed with epoxy glue to make the mount rigid and give it its final shape. The picture to the right shows the sketch of the hand mount, view from the top, with all dimensions.

Finger exoskeleton

Last semester, our team designed and 3D printed a first exoskeleton prototype. However, after testing, we realized that this first prototype did not meet our expectation to provide a realistic grip and touch feeling to the user: while performing a "grab" motion, the user's finger would slightly shake and swing around the arc constrained by the wire, breaking the immersion. After exploring different concepts for a second prototype during the summer and early September, we came up with a glove-like design, that we named the "caterpillar" solution. During September, our team worked on the CAD of this new version of the exoskeleton. As we almost had no experience with CADing, time was invested in learning the FreeCAD tool.

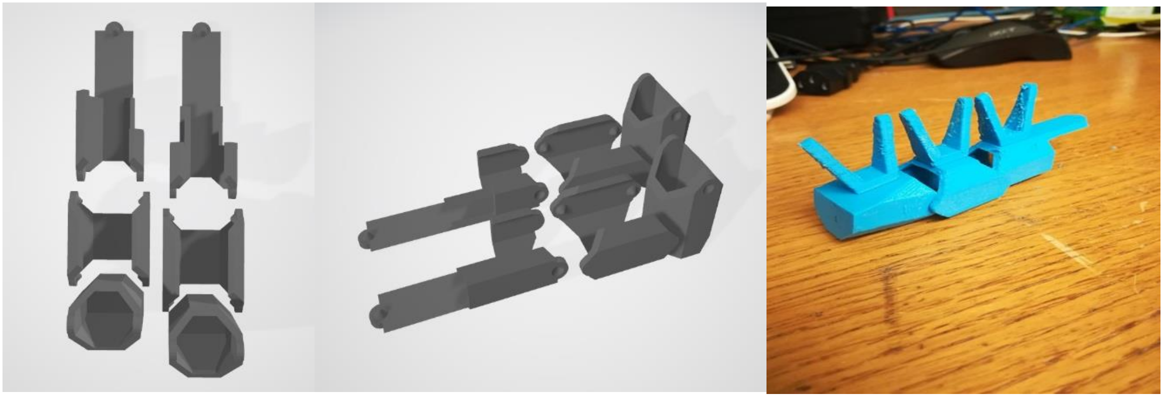


Figure 9, 10 & 11: Finger Exoskeleton

Before the 3D print of the entire “caterpillar” design, we only printed and assembled the index part to verify the scale and its proper behavior. A picture of this partial print can be seen on the right, after its assembly. As for the actuator, we are using a low profile 5V servo metal gear motor [10] capable of pulling 3 to 3.5 kg/cm which by testing, is more than enough to counteract one finger’s force. We are using one servo per finger we want to apply force feedback to.

Knuckle mechanism

The knuckle mechanism is essential as it links the finger skeleton and the hound mount. It must also allow the user to bend his fingers. The design of the knuckle mechanism was firstly thermocut in Styrofoam, before a CAD was made. The 3D model is shown below with two screenshots of the FREEcad design.

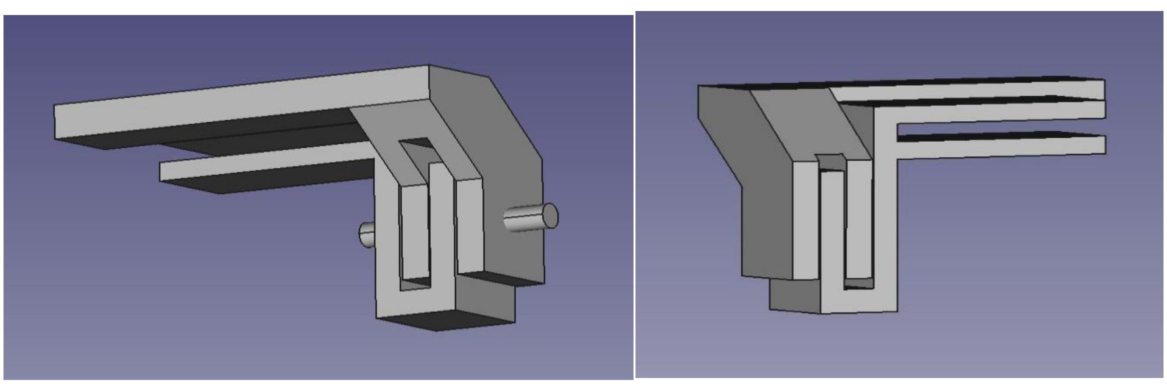


Figure 12 & 13: Knuckle Mechanism 3D View

The pictures above show a FREEcad 3D view of the knuckle mechanism. It is composed of three parts: a static part (fixed on the hand mount), a rotating part and the bearing.

The bearing provides a rotation axis and allows the rotation between the static and rotating part to take place. When designing the bearing, the main focus was to keep the bearing as low-profile as possible to reduce the bulkiness of the exoskeleton, as well as reducing the friction between the two parts.

The implemented solution consists of two hollow "telescoping" brass rods, one inserted into the other. Among all the rods available at the workshop, we selected a matching pair with a diameter that is large enough to allow an easy machining and crafting. The specifications of the two rods is given below:

- Smaller radius rod:
  0.188" outside diameter / 0.160" inside diameter
  4.775mm outside diameter / 4.064mm inside diameter (equivalent in millimeters)
- Larger radius rod:
  0.219" outside diameter / 0.191" inside diameter
  5.563mm outside diameter / 4.851mm inside diameter (equivalent in millimeters)

The larger radius rod was glued to the 3D printed rotating part, while the smaller radius rod was glued to the fixed part. Therefore, holes of diameters 0.188" and 0.219" were drilled in the fixed and in the rotating part respectively.

Some pictures of the crafting are provided below. The picture on the left shows the preliminary design, thermocut in Styrofoam. The picture in the middle illustrates the cutting operation of the rods. The picture on the right shows the drilling of the 3D printed parts to allow the proper insertion of the rods.

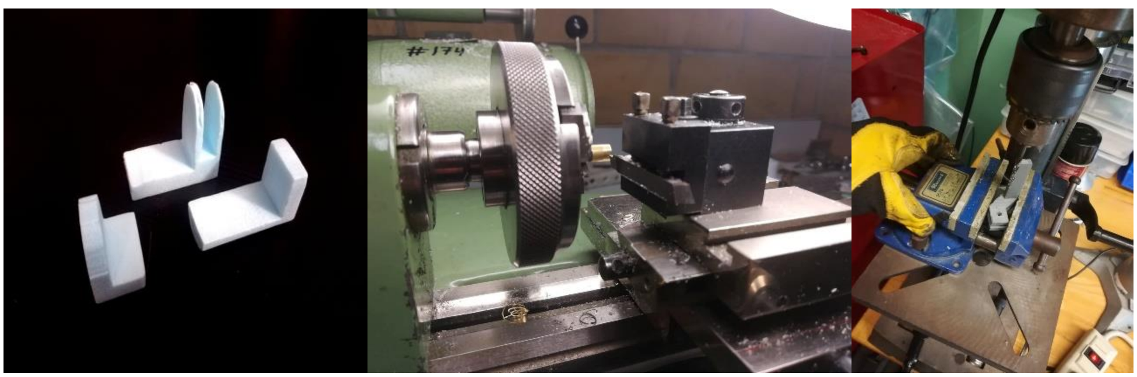


Figure 14, 15 & 16: Knuckle Mechanism Manufacturing

Thumb

Due to the complexity of the thumb's degree of freedom, our team had a very difficult time trying to find a force feedback solution for it. We discussed this problem with Don Pavlasek who specializes in mechanical systems at McGill university. However, we could not arrive at a solution and therefore decided to constrain the thumb rather than waste more time on it. With the help of Mr. Pavlasek, we were able to find a simple solution to immobilize the thumb. The system is comprised of a long and narrow metal sheet that is bent in half for ¾ of its length for rigidity that goes along the thumb and molds all the way to the side of the start of the forearm. The metal sheet is attached using Velcro to the thumb and to the wrist.

Manufacturing problems encountered

Our team encountered a lot of issues coming from the 3D printer. A lot of students from all faculties have access to the 3D printers, everyone printing with different printer settings. Properly calibrating the 3D printer at every use was a big challenge for us. A poor calibration or wrong settings usually resulted in printing failures.

On top of that, nozzle clogging and under extrusion also resulted in failed prints. The pictures on the right was taken when printing the middle finger parts. The nozzle clogged during the operation, after 2h30 of printing. These numerous issues we had to deal with slowed down the manufacturing process.

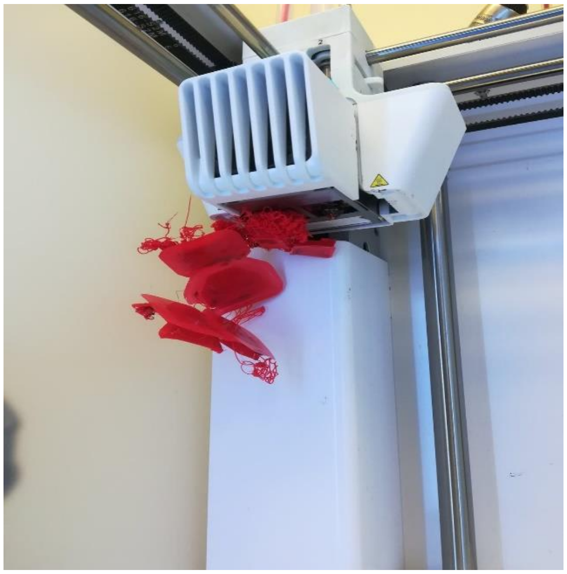


Figure 17: Clogged Nozzle

DESIGN PART 3 – VR ENVIRONMENT DESIGN

Software Dependencies

The software used are the following with their respective libraries and plugins:

- Unity3D v.2018.2.13f1 [11]
    - Data Streaming for Motive: Direct Unity C# client for Optitrack Motive [12]
    - Arduino - EMS communication: openEMSstim[9]
- OptiTrack Motive v1.5.0 with NatNet Streaming Module v.2.5.0.0 [13]
- Arduino IDE v.1.8.7 [14]
    - Official Servo Library [15]

Architecture

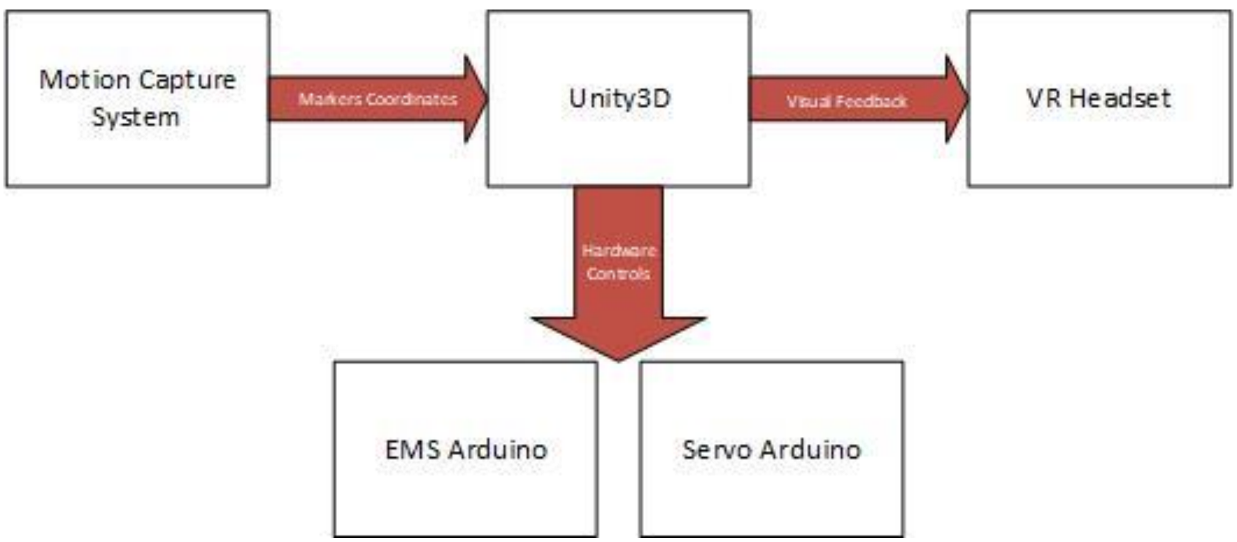


Figure 18: System Architecture

As seen in the *fig. 18*, Unity3D is the heart of the system. The reason behind choosing this software is because of its vast integration with different modules such as VR or hardware communication by simply adding plugins to the project. Furthermore, our team has already previously worked with the software.

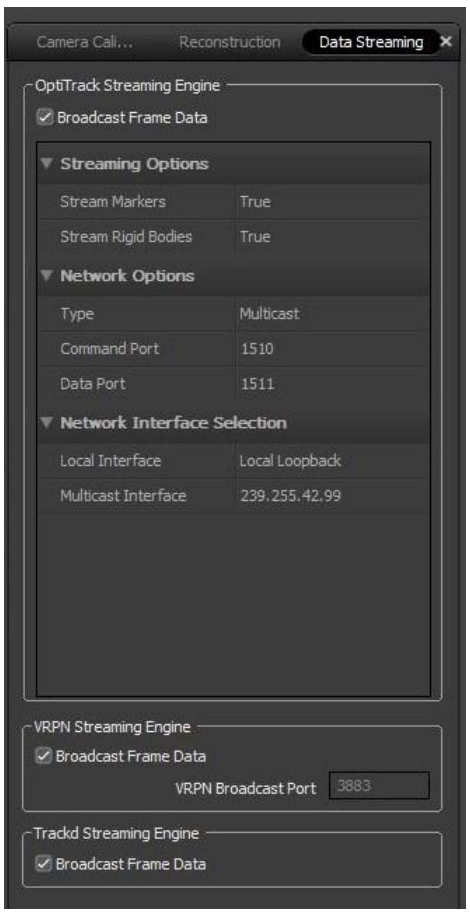
Integration with hardware

Arduinos are perfect lightweight and cheap microcontrollers to use. In our scenario, we only needed to actuate 5V servo motors with a PWM signal. The Arduino Nano [16] was the perfect candidate. Furthermore, Pedro Lopes' openEMSstim[9] kit also uses an Arduino Nano which makes the integration easier since all microcontrollers are standardized.

Both boards communicate via USB serial communication to the game engine. As the first complete prototype, having them wired to the computer would ensure a reliable communication and less debugging to do on the hardware side. However, the openEMSstim [9] kit already comes equipped with Bluetooth communication. Thus, to make the system completely wireless, we would just need to add a Bluetooth module to the servo-arduino and ensure the computer running Unity3D has Bluetooth connectivity.

Motion Capture

Out of the different tracking solutions proposed in the *Background* section, Motion Capture seemed the most suitable for our application allowing us to track any body parts with markers. In addition, we had access to the OptiTrack MoCap system in our lab. OptiTrack uses their Motive software to gather data from the cameras and interpret them. Furthermore, there are plugins allowing strong integration with Unity3D. Since, we were using an outdated Motive license, we had to fall back to a third-party plugin from XmanLCH [17] which supports NatNet v2.5.0.0. To make both software talk to each other, they need to have the same parameters as seen in *fig. 19 & 20*.



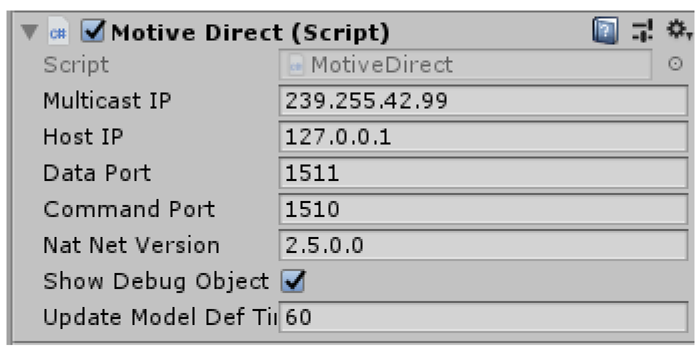


Figure 20: Unity Data Streaming Parameters

Figure 19: Motive Data Streaming Parameters

In our setup, we placed a total of 5 cameras across the room. With this configuration, we were able to have a decent tracking zone of $2m^2$ represented by the blue rectangle in *fig. 21*.

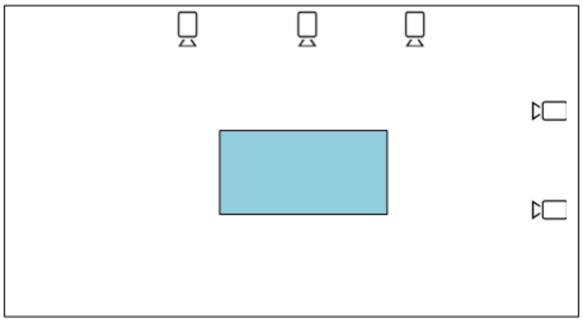


Figure 21: Camera Setup

Finally, to track the user's movement, we are using 5 markers as seen in *fig. 22*: 3 in red create the rigid body within Motive to track the hand's xyz-coordinates as well as its rotation and 2 free markers in green placed on the index and thumb to check if the user is grabbing or not. From the plugin found on GitHub, a few modifications had to be made to be able to track free markers. These modifications can be found in the *Appendix F* and the GitHub repository in *Appendix E*.

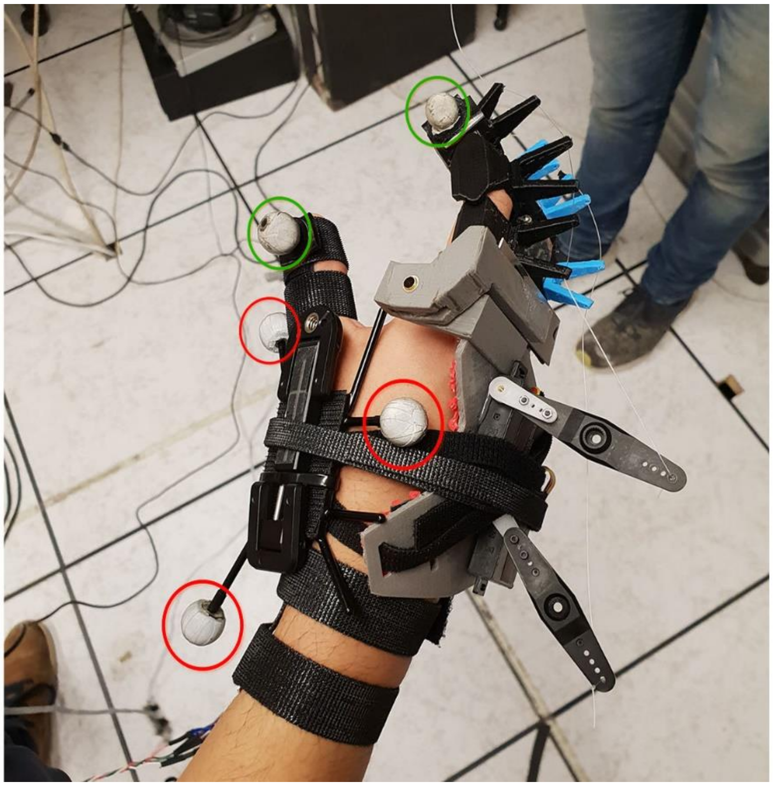


Figure 22: MoCap Markers Setup

VR HMD

For the visual feedback, we are using the Acer Mixed Reality Headset which doesn't require any external hardware for tracking. It is solely using a stereo integrated camera to track both xyz-coordinates as well as rotation. Furthermore, Unity3D only supports SteamVR [18] out of the box whereas Acer's HMD uses Microsoft's Mixed Reality [19] interface. Therefore, we are using the official Mixed Reality Unity plugin provided by Microsoft [20]. As the HMD has its own tracking sensors, we do not need to MoCap to track it.

Figure 23: User with VR HMD and Force Feedback system

Known Problems

Since we are using an older version of Motive, the third-party Unity3D plugin is not very stable. To open the data stream on Motive, we first need to run a more recent Unity3D plugin [21]. By running the scene in the game engine, the Motive NET indicator in the bottom right corner as seen in *fig 24.* will turn from yellow to green: this means Motive is now streaming data. Once green, we can open the actual Unity3D project and data from Motive should be sent to the game engine.

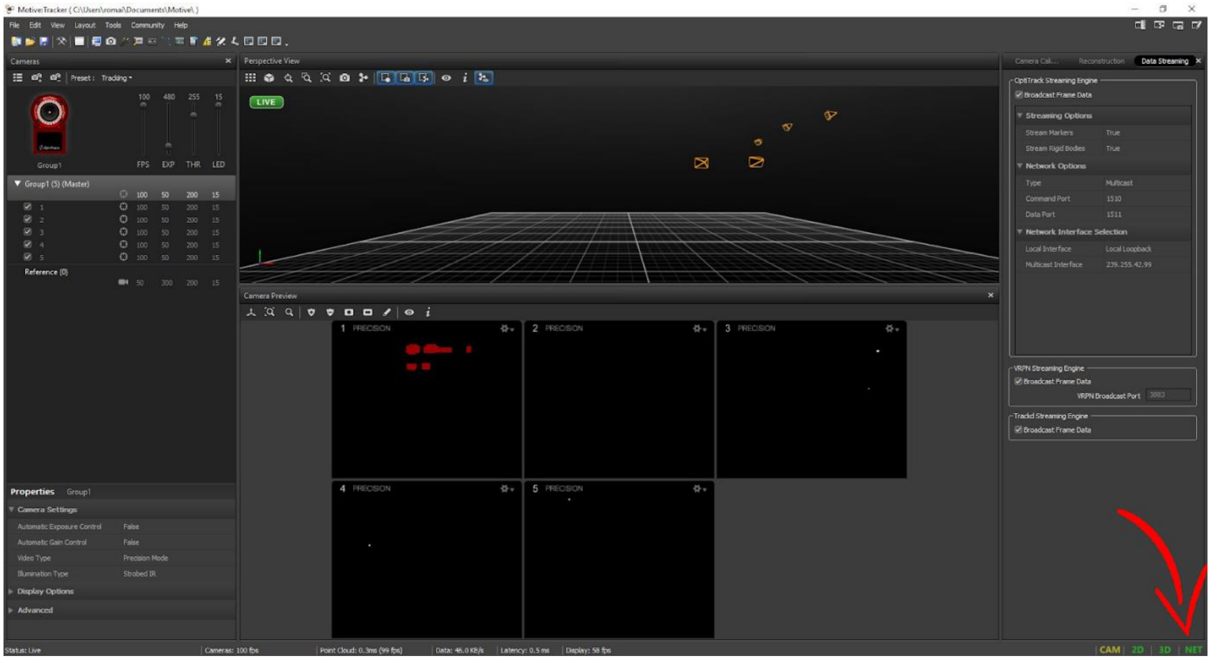


Figure 24: Motive NET Indicator

Moreover, when running the Unity3D scene, because of the errors the plugin is throwing, the program crashes time to time. Since it is only on the game engine side, we can just relaunch the project and run the scene again without redoing the previously mentioned procedure. These errors might be caused by lost of marker tracking.

TESTING

We designed an experiment intended to help us learn how task performance in VR is affected by the two feedback mechanisms, as assessed by:

1. efficiency (time),
2. precision (trajectory),
3. load factors (as reported through self-evaluation)
4. muscle fatigue (measured via electromyography)

Procedure

1. Participants sign a consent form (Annex B) and complete a pre-experiment questionnaire (Annex C).
2. They put on the VR headset, exoskeleton, and the experimenter attaches the pre-gelled (single-use) EMS electrodes to the triceps of the participant's right arm, and EMG sensor, adjacent to the electrodes. For hygienic purposes, alcohol is used to clean the area of each participant's arm on which EMG the sensor is placed. The sensor itself is also cleaned with alcohol after each participant.
3. They complete a practice round to familiarize themselves with the feedback in each of the experimental conditions:

   A. no force feedback (VR visuals environment only)
   B. exoskeleton
   C. EMS
   D. both exoskeleton and EMS

4. For each experimental condition, ordered by a Latin square design, participants complete three trials of the task:

   a. Each trial is timed, and the trajectories of the participant's hand and virtual bottle are recorded. The EMG sensor records muscle fatigue as the participant complete the task.
   b. Following each block of trials for a single condition, a NASA TLX workload measurement questionnaire is administered for participants to self-evaluate the mental demands, physical demands, temporal demands, perceived performance, effort, and frustration level associated with each condition.

The scenario involves picking up and lifting a virtual bottle filled with water and moving it from its original location to a target.

5. Participants complete a post-experiment questionnaire (Annex D).

Ethics Approval

The team had to write an application to receive approval from the ethics committee at McGill to be able to experiment on participants. Before sending the application, all three members also had to pass the Government of Canada's TCPS 2 ethics tutorial. The application took some time to put together because, in addition to identifying and discussing all the different ethical implications involved in our project, it required the completion of many documents: the experimental procedure, testing documents and questionnaires, a consent form, and an experiment advertisement (Annex A). Completing the application was slow because our designs were still experiencing some changes continuously. However, the application was necessary to complete as early as possible because the ethics committee review was predicted to take approximately three weeks. We received approval on the 6th of November, only a few days after sending the application. We visited the ethics office to review the application before sending it, which is why we believe the review went much faster than expected.

Pre-testing sessions

The team was only able to complete the full assembly of the design on the 25th of November. Full testing on participants could thus not be completed on time. However, preliminary testing done on two Shared Reality Lab members and another student at McGill were performed for feedback and review of the design in preparation for actual testing.

Preliminary Testing Results

Due to time constraints, only three participants were tested. Moreover, the NASA TLX documents weren't administered, but the questionnaires were. These preliminary tests were just used to receive general feedback from participants. We simply allowed the three users to try out the three different configurations (Exoskeleton only, EMS and Exoskeleton, and motion capture only) at a simple scenario. The scenario involved picking up a bottle in virtual reality and placing it from a blue target to a red target. The questionnaire results are displayed in the table and the graph below.

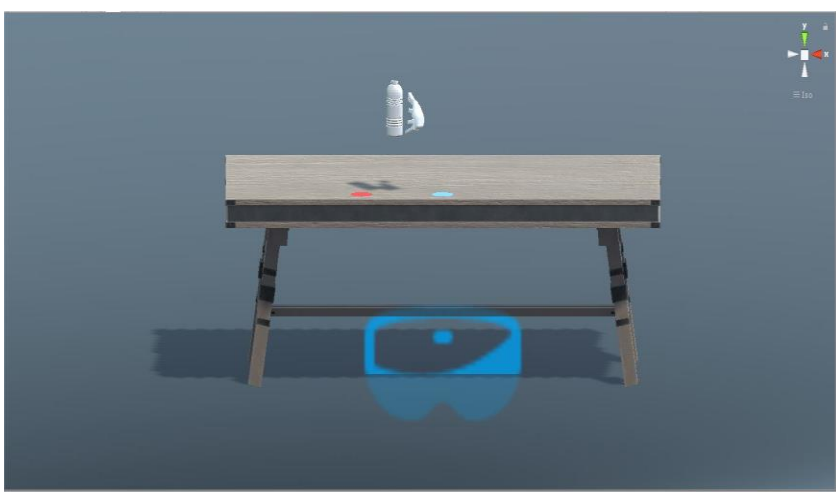


Figure 25: VR Environment for Bottle Scenario

	Point average		
	Exoskeleton only	MOCAP only	Exoskeleton and EMS
1. Feeling of safety 1 = poor 5 = excellent	4.3	4.7	3.3
2. Clarity of interface/3D environment 1 = poor 5 = excellent	3.7	3.7	3.7
3. Hand fatigue 1 = very tiring 5 = no fatigue	4.3	5.0	4.3
4. Forearm fatigue 1 = very tiring 5 = no fatigue	4.3	5.0	4.3
5. Upper arm fatigue 1 = very tiring 5 = no fatigue	4.3	4.7	2.0
6. Ease of getting used to 1 = poor 5 = excellent	3.7	3.3	3.7
7. Intuitiveness of interaction 1 = poor 5 = excellent	3.3	2.3	3.3
8. General preference 1 = least 5 = most	4.0	2.7	4.3

9. Realism of grabbing motion 1 = poor 5 = excellent	2.3
10. Realism of weight representation 1 = poor 5 = excellent	2.3

Figure 26: Questionnaire Point Average Table

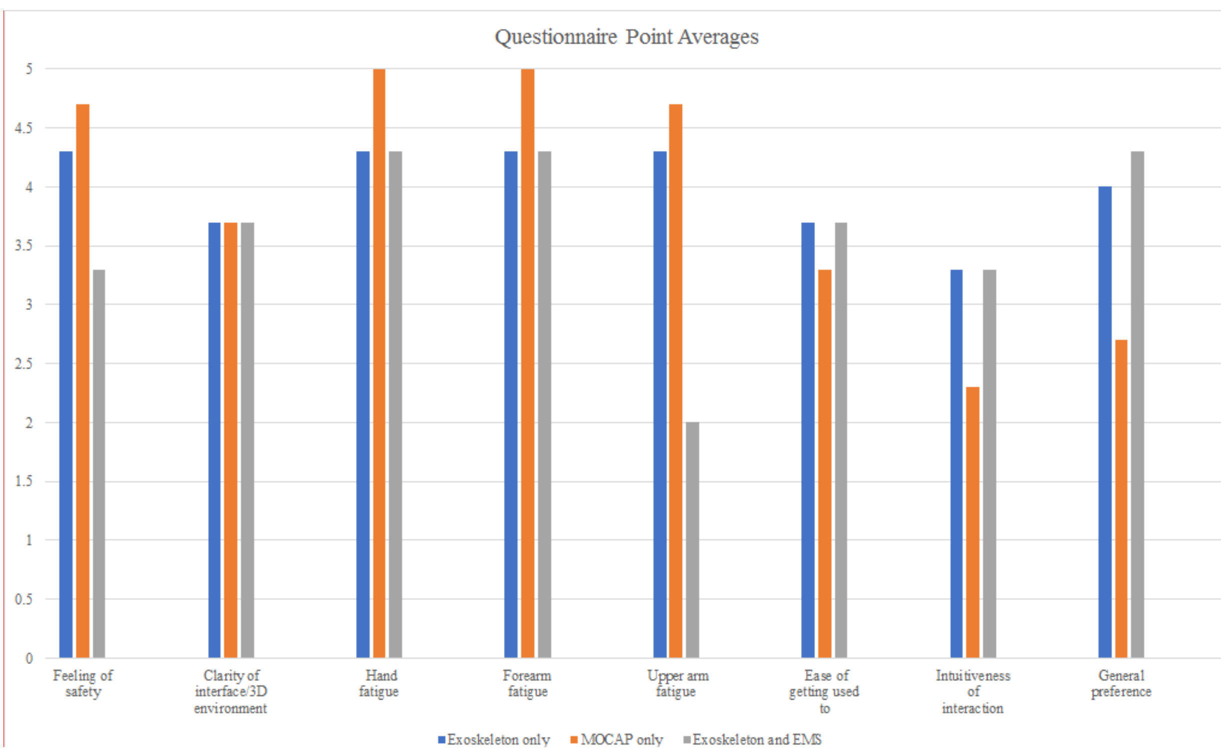


Figure 27: Questionnaire Point Average Graph

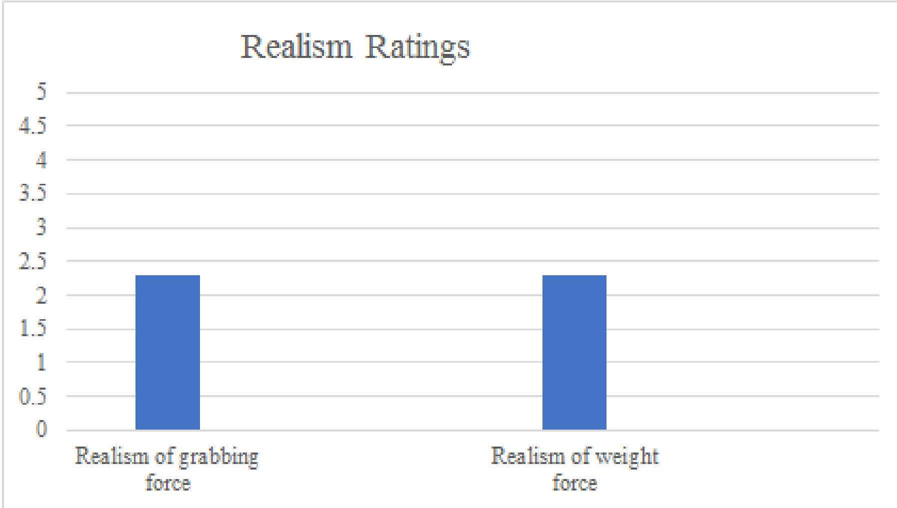


Figure 28: Realism Ratings Graph

From the Questionnaire Point Averages graph we can see that the average feeling of safety for the combined system is at 3.3 - compared to 4.3 for the exoskeleton only - which suggests that the participants did not feel a high level of safety when experiencing the EMS. This result was expected to some extent because EMS causes involuntary muscle movement. The participants also clearly experienced strong upper arm fatigue by using the combined system, caused by the EMS.

In five out of the eight result, we can see that the exoskeleton and the combined system have the same point average. The exoskeleton however, beats the combined system in feeling of safety (4.3 vs 3.3) and upper arm fatigue (4.3 vs 3.0). This suggests that adding the EMS might create a more negative downside than a positive one. However, the study suggests that the combined system was more intuitive than when using MOCAP on its own and that participants had a general preference for the combined EMS and exoskeleton system.

It was interesting to hear other comments from participants, especially regarding the EMS that some had never tried before. One participant said that the EMS provided a strong sensation of effort, which contributed to the realism of the interaction to some extent, but without necessarily creating a realistic representation of gravity. Two participants said that the feeling of vibration from the EMS was more distracting than it was contributing to the feeling of realism. One of these two participants had already experienced EMS many times before. They also commented that they rated the realism of grabbing quite low because, although the system provided a strong force feedback for the fingers, the actual feeling of contact/touch with the bottle was absent.

IMPACT ON SOCIETY AND ENVIRONMENT

“The potential for VR to help us understand and transform ourselves and the world around us is limitless. It is crucial that the VR industry comes together in these formative years to fully leverage this potential for social good,” said Ylva Hansdotter, Head of VR for Impact, HTC Vive. Being able to virtualize and shape any environment can help the society in many ways. In the health industry, doctors helped partially, and completely paralyzed patient regain some feeling in their legs after using an exoskeleton and VR [4]. Additionally, by implementing hand and arm force feedback, operators can remotely use precision to control heavy machinery under a safe environment.

The choice of materials for the prototype were made with the impact on the environmental impact in mind. The exoskeleton frame was made in PLA due to material properties but also of its environmental impact. PLA is made out fermented plant starch instead of being petroleum-based like ABS plastic. If incinerated, PLA will not emit toxic fumes. Furthermore, the carbon footprint of this renewable resource is twice as much efficient than ABS (1.9kg CO_2/kg plastic versus 3.4kg CO_2/kg plastic for ABS). Other hardware has been either recycled from previous projects or selected carefully before ordering them.

Using the EMS technology requires certain care. If misused, the user can suffer severe injuries and in the worst case, lead to a cardiac arrest. The members of the team undertook trainings and follow strict procedures when developing with the EMS kit. During any experimentations or demonstrations, a trained member will be supervising and ensuring that the user is safe before, during and after the process.

REPORT ON TEAMWORK

In an open-ended project like ours, one of the key skills is to keep communicating and sharing ideas. Amongst the proposed different choices, we need to narrow down the most realistic design we can achieve with the available resources. Furthermore, since each member of our team have different skills sets, we made sure we allocate suitable tasks to everyone so that we can focus on higher level designs rather than learning new tools.

The tasks were split as follows:

- Augustin worked on the testing and assembly of the exoskeleton
- Clement worked on the exoskeleton design and EMS investigation
- Romain worked on the VR environment and overall integration

CONCLUSION

During the last semester of the project, our team was able to design and assemble a prototype of an untethered force feedback system. We modeled, printed and manufactured a custom hand exoskeleton to provide a force feedback to the fingers and as well as experimented the effect of EMS on different parts of the arm. With these results, we then integrated them into the VR environment in order to perform some tests on subjects and gather data to further improve the system.

The team completed an ethics training and through an application received approval from the Ethics Committee at McGill for human testing. During the tests, the subjects were asked to pick up and place a water bottle from a point A to B. In the experiment, the exoskeleton renders the shape of the bottle whereas the EMS system simulates the weight. Furthermore, the user's movement are tracked using motion capture. Various testing documents and procedures were created to acquire results from participants. Preliminary testing was completed, and feedback was received from six participants (although only three answered the full questionnaire).

Many improvements can be made on our design. For example, the exoskeleton for only two fingers was built and tested, so in the future the exoskeleton can be improved to accommodate two other fingers. In addition, due to the complexity of the motion of the thumb, it was immobilized in our prototype. Hence further research includes finding a solution for force feedback on the thumb. Since our device is an early prototype, easy access materials were used. We could thus improve the sturdiness, compactness and overall comfort of the exoskeleton by investigating into more appropriate materials.

From our results gathered from tests, it also seems that the actual implementation of EMS doesn't bring more immersion to our system. Indeed, participants reported that the EMS provides a general effort feeling rather than a sensation of weight. Moreover, some participants found the electric impulses too distracting and unpleasant to convey a realistic feeling. We could thus do some more research on how the weight simulation can be improved by adjusting the electric impulse frequency and wave shape for example. This could help in making the EMS experience more comfortable and less distracting.

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APPENDICES

Appendix A: Advertisement for Participation

Hello! We are a small team of undergraduate students in Computer and Electrical Engineering working on a term project in Virtual Reality. We are looking for people to participate in our experiment! If you are a McGill student and could be interested, please read below for more information:

The purpose of our study is to explore the potential of force feedback in Virtual Reality with a system comprised of a hand exoskeleton and electrical muscle stimulation (EMS) applied to the triceps. Force feedback is the idea of a physical force being exerted against one's body in reaction to that person's action.

The experiment employs a VR headset, a hand exoskeleton prototype developed by the research team, and an EMS kit. This equipment will allow you to interact with the VR environment. You task involves carrying out several rounds of picking up and moving an object in a virtual reality environment, under different feedback conditions.

You will be receiving electrical muscle stimulation. This involves delivery of small electrical currents to stimulate and activate your muscles. So if you have been diagnosed with any cardiac conditions, or if you have any electrical implants in your body (e.g., pacemaker), you are not allowed to participate.

The study requires approximately one and a half hours of your time and is done in one session only!

The only other requirements is that you must be right handed and have an index finger circumference between 1.6 and 2.0cm measured at the base of the finger (because our prototype can only fit such a size).

Participation is voluntary and your data will be collected anonymously! The tests will take place on the McGill University campus in McConnell Building. There is no monetary compensation involved but we simply hope that you receive an interesting experience with our VR force feedback system 😊

If you are interested in participating or would simply like more information, please contact the research team below!:

Augustin Legrand: augustin.legrand@mail.mcgill.ca
Romain Nith: romain.nith@mail.mcgill.ca
Clément Fournier: clement.fournier@mail.mcgill.ca

Appendix B: Participant Consent Form

McGill

Department of Electrical and Computer Engineering

You are invited to participate in an experiment run by Augustin Legrand (augustin.legrand@mail.mcgill.ca), Clement Fournier (clement.fournier@mail.mcgill.ca), and Romain Nith (romain.nith@mail.mcgill.ca), who are students in the Department of Electrical and Computer Engineering at McGill University, under the supervision of Prof. Jeremy Cooperstock (jer@cim.mcgill.ca). The purpose of the study is to explore the potential of force feedback in Virtual Reality with a system comprised of a hand exoskeleton and electrical muscle stimulation (EMS) applied to the triceps.

The experiment employs a VR headset, a hand exoskeleton prototype developed by the research team, and an EMS kit. This equipment will allow you to interact with the VR environment. You will wear the VR headset and the exoskeleton will be set up on your hand, with the base secured to the forearm using Velcro. The EMS electrodes will be attached to your arm using pre-gelled (single-use) electrodes. Alcohol will be used to clean the area of your arm on which an EMG sensor will be placed to measure muscle fatigue. You will be asked to carry out several rounds of picking up and moving an object in a virtual reality environment, under different feedback conditions. After the experiment, you will be asked to complete a questionnaire on your experience and a self-evaluation form.

You will be receiving electrical muscle stimulation. This involves delivery of small electrical currents to stimulate and activate your muscles. Physiologists frequently use this type of stimulation during physical rehabilitation. This type of apparatus has been identified by the FDA as a "non-significant risk device". Although the research team have been trained to follow safety measures and procedures to reduce risks to a minimal level, you should be aware that inappropriate use of this equipment could potentially cause mild burns, skin irritations and bruising where electrodes are located, or death.

The study requires approximately one and a half hours of your time.

We will not collect any personal identifying information from you during the experiment, nor reveal your identity to anyone outside of the experimenters and their supervisor. You will be assigned a random ID number, and all your collected data will be associated only with this ID. Only the research investigators and their supervisor will have access to the raw data, which will be kept securely on a password protected computer. Dissemination of the results will be done primarily via an academic research paper and the Design Project presentation at the end of the semester.

Participation is voluntary. The tests take place on the McGill University campus. There is no monetary compensation involved, and we simply hope that you receive an interesting experience with our VR force feedback system. You are free to stop participation in this study at any time, and to request that your data be deleted before you complete the experiment. However, because we will not retain a data key, associating your name with your assigned ID, it will not subsequently be possible for us to identify or delete your data.

Should you have any questions about this study, you may contact the research supervisor, Prof. Jeremy Cooperstock at jer@cim.mcgill.ca or by telephone at 514-398-5992.

If you have any ethical concerns or complaints about your participation in this study, and want to speak with someone not on the research team, please contact the McGill Ethics Manager at 514-398-6831 or lynda.mcneil@mcgill.ca".

Please sign below if you have read the above information and consent to participate in this study. Agreeing to participate in this study does not waive any of your rights or release the researchers from their responsibilities. A copy of this consent form will be given to you and the researcher will keep a copy.

Participant's Name: (please print) ______________________________________

Participant's Signature: ________________________________ Date: ____________

Appendix C: Pre-experiment Questionnaire

ID: __________

Age: _____
Gender:

1. How often do you play video games? (daily, a few times a week, once a month, almost never)?

2. How familiar are you with VR/AR systems (e.g., Oculus Rift, Samsung Gear etc.)? Please describe the equipment used and the type of VR/AR experience (e.g., for gaming, practice simulation, etc.)

3. Approximately how many hours per week do you typically spend playing a sport or engaged in a physical activity? Please describe the type of sport/physical activity.

Appendix D: Pre-experiment Questionnaire

ID: __________

Please write the letters "H" (hand exoskeleton only), "E" (electrical muscle stimulation only) and "B" (both hand exoskeleton and electrical muscle stimulation) at the positions on the scale that correspond best to your feelings about each of the following aspects of your experience.

1. Feeling of safety

	1	2	3	4	5	
Poor	○	○	○	○	○	**Excellent**

2. Clarity of interface/3D environment

	1	2	3	4	5	
Poor	○	○	○	○	○	**Excellent**

3. Hand fatigue

	1	2	3	4	5	
Very tiring	○	○	○	○	○	**No fatigue**

4. Forearm fatigue

	1	2	3	4	5	
Very tiring	○	○	○	○	○	**No fatigue**

5. Upper arm fatigue

	1	2	3	4	5	
Very tiring	○	○	○	○	○	**No fatigue**

6. Ease of getting used to

	1	2	3	4	5	
Poor	○	○	○	○	○	**Excellent**

7. Intuitiveness of interaction

	1	2	3	4	5	
Poor	●	●	●	●	●	**Excellent**

8. General preference for the system

	1	2	3	4	5	
Least	●	●	●	●	●	**Most**

Please comment on why you preferred one particular experimental condition of force feedback the most and why you least preferred another condition.

Appendix E: Team's Force Feedback Project GitHub Repository

https://github.com/romnith/Force-Feedback

Appendix F: Modified Code from MotiveDirect Plugin

```
}
Dictionary<int, Transform> transformDict = null;
if (!markerSetIDtoTransfrom.TryGetValue(setPrefix, out transformDict))
{
    transformDict = new Dictionary<int, Transform>();
    markerSetIDtoTransfrom[setPrefix] = transformDict;
}
// clean the tracking flag
foreach(Transform mkTransform in transformDict.Values)
{
    mkTransform.tag = "untracked";
}

// Reset index counter
ulmIndex = 0;

// Unlabeled markers:
foreach (Vector3 ulm in msg.other_markers)
{
    if(ulmIndex == 0)
    {
        marker0 = ulm;
    }
    else
    {
        marker1 = ulm;
    }

    // Update index for next marker
    ulmIndex++;
}

// Calculate distance between the 2 unlabeled markers
markerDistance = Vector3.Distance(marker0, marker1);
//Debug.Log("Distance: " + Vector3.Distance(marker0, marker1));

foreach (LabeledMarker lmk in msg.labeled_markers)
{
    //Debug.Log(lmk);
    int setID = HighWord(lmk.id);
    int mkID = LowWord(lmk.id);
    if (setID != 0) continue; //skip markers that are already included in rigidbodies/skeletons/m

    string mkName = string.Concat(setPrefix,"_", mkID.ToString());
    Transform mkTransform = null;
```