

Comfortable manipulation of a virtual gearshift prototype with haptic feedback

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ABSTRACT

Improving quality, design and comfort is very important for high-technology companies in order to stay competitive against the other enterprises. A present problem is that the new physical dedicated prototypes they need to create for the tests are very expensive and time-consuming [5]. Another solution would be to create virtual and touchable prototypes. We would work with the Haptic Workstation™ provided by Immersion Corporation (http://www.immersion.com/3d/docs/HWS2_datasheet.pdf) for the simulations. The user would be in a fully immersive, virtual and flexible environment with haptic feedback on his/her arms and fingers.

We have developed with the help of RENAULT TRUCKS Cockpit Studies Department a completely virtual cockpit with a touchable gearbox prototype. At the beginning we only wanted to test the feasibility of such an application but in a second time we also made some biometric tests with the help of an ElectroMyoGraph (EMG) to verify the user comfort and his belief in the simulation.

Keywords: haptic, 2 hand haptic feedback, driving simulation, comfort, gravity, EMG, believability

1 INTRODUCTION

The goal of this article is to show the feasibility, with a reasonable accuracy, to simulate the gear shifting with a passive haptic device. This project was achieved at the Virtual Reality Laboratory (EPFL, Switzerland) (<http://vrlab.epfl.ch>) in collaboration with RENAULT TRUCKS Cockpit Studies Department (<http://www.volvo.com/trucks/france-market/fr-fr/>) who provided us the 3D models of the cockpit.

We build then a completely virtual truck cockpit with mobile and touchable objects such as the steering-wheel and the gearbox. In this article we focus on the gear shifting we can also turn the steering-wheel. The user, during the simulation, can take the lever and shift from a gear to another one with by providing a realistic muscular effort with his arm due to the haptic feedback. In order to improve the immersive side of this application, we then created a map of a city and located the cockpit at a crossroad.



Figure 1: Views of our application cockpit

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We have made a believable and comfortable gear shifting simulation with the Haptic Workstation (<http://www.immersion.com/3d/support/documentation.php>).

By comfortable, we mean that the user does not have to carry the weight of the exoskeleton such as in the “Virtual” [8] project in which the simulation became quickly painful for the user. Indeed, we worked with the concept of “gravity compensation” developed in [11] with the framework of the mediators to continually apply a support force on the user arms. The user comfort is then greatly improved, which increases the simulation believability. We will also introduce a special force which reduces a lot the muscular effort of the deltoid and ameliorate a lot the user comfort.

We insist also on the flexible side of the cockpit to be able to move most of the elements and the user position. We will then be able to test new locations for e.g. the gearbox, buttons on the dashboard, etc. in order to improve the ergonomics of truck cockpit. Moreover, as we are working with the Haptic Workstation™, the user can interact with both hands in the virtual environment. It is shown in [7] that it helps a lot the user to feel at ease with the simulation.

To introduce the work we present in this article, we will first make a related work survey showing you the improvements supplied by our application. We present you briefly the used peripherals: a Head-Mounted Display (HMD) combined with a Head-Tracker and the Haptic Workstation™. An overview of the system architecture will be done and we then focus on the force feedback creation. This will include a presentation of the used forces and the graphical user interfaces we created to control the haptic feedback in real time. We finally show you the tests we made, with biometric values, on the comfort and believability of the simulation concluding with a small presentation of the future works and uses of the application.

2 SURVEY

So far, it was mandatory to physically build a dedicated hardware in order to simulate the gear shifting. This was really expensive and time-consuming.

Some dedicated haptic interfaces [5] such as a gearbox lever prototype were proposed. Concerning the driving simulation, it seems to be interesting because we can change the mechanical values without having to build a new gearbox. But with this method, we have to physically build every element of the cockpit and to integrate them before we can make some tests.

Within the framework of the mediators [6], completely virtual commands were used to drive a car. There was no need to build physical prototypes such as a gearbox or a steering-wheel but the driving controls (two levers) were not very realistic intuitive and realistic for a driving simulation.

The project “Virtual” [8] tried to create a driving lessons simulation. There were fully virtual and realistic driving controls (except the pedals) with the help of a haptic device allowing the use of only one arm in the simulation. As we can see in [9] the use of one’s non dominant hand can be very interesting and more immersive for the user. Moreover it is more common to drive with two hand (with at least one on the steering-wheel). They concluded that driving simulations, were not really interesting because of the comfort lack due to the exoskeleton weight the user had to carry during the sim-

ulation.

Last year, a kind of “gravity compensation force” was proposed in [11]. We will then use this concept in our application to show it is possible to simulate a comfortable manipulation of a virtual gear-box (and steering-wheel) prototype with a haptic feedback on the arms and fingers due to the Haptic WorkstationTM. In our application, we focus on the user comfort the believability of the simulation. The user can thus use both hands without having to carry the exoskeleton weight in our simulation and we made some tests with the help of an EMG to verify if we reached, with a reasonable accuracy, our goals.

3 SYSTEM ARCHITECTURE

This section describes the software that allows the simulation of gear shifting. We will first make a short description of the peripherals we used concluding with the architecture of the classes.

3.1 Used peripherals

We present here after the peripherals we used for this application. To provide a haptic feedback, we show you the Haptic WorkstationTM. Concerning the visual material, we used an HMD combined with a Head-Tracker.

3.1.1 Haptic WorkstationTM

In order to get a more immersive and interactive experience, we used our Haptic WorkstationTM. It is composed of two exoskeleton over the arms providing the position of the hands and allowing to apply forces on the arms. There are also force-reflecting exoskeletons that fit over the hand and add resistive force feedback to each finger. To get the hands and fingers position and orientation, we use CyberGlovesTM you can see on the picture below. It provides a real-time two-handed evaluation of 3D models. In our case, the user can literally hang his/her hand on the virtual gearshift lever and he/she will feel the mandatory pressure to hold his/her hands in place. We will then experience the effort needed to shift the gears.



Figure 2: Used hardware

3.1.2 Head-Mounted DisplayTM combined with a head-tracker

This part introduces the other hardware we used: a Head-Mounted DisplayTM (HMD) (<http://www.est-kl.com/hardware/hmd/kaiser/proviewxl3550.pdf>) combined with a head tracker. We have a HMD Kaiser ProViewTM XL 50 with a resolution of 1024 per 768 pixels and a refresh rate of 60Hz. We use it to show stereoscopic images by displaying an offset image to each eye. Lenses are used to give the perception that the images are coming from a greater distance, to prevent eye strain. The head tracker (small cube you can see on the top of the HMD) allows to get the orientation of the user head. The user can

then naturally “look around” in the virtual environment by moving his/her head without the need for a separate controller. With this hardware, the user can see everything as if he/she were in the cockpit.

3.2 Architecture of the classes

This subsection introduces the design we used for the classes of our application.

In order to make this application as generic as possible by allowing the add of future elements (mobile or not) and the change of the scenery (e.g. a car cockpit, a room,...) we decided to create one class per element of the scene. The first one represents the immobile elements of the scene: the cockpit skeleton combined with the landscape. Another one is for the gear box which we will manipulate. There is also one for the steering wheel we will touch and turn in a further application. We then have 2 “visual” classes: one for the camera and another to manage in real time the 2D graphical user interfaces which control the haptic feedback. Finally, a class for the thread that computes the forces to apply on the user arm and fingers and special class for the sensitive variables which need to be carefully accessed because several threads read and write them. Indeed, in order to preserve the frame rate we used three threads: the visual feedback, the haptic feedback and the calculation of the forces to apply.

We can then easily add new touchable elements to our cockpit. Moreover it is easy to combine another application (e.g. turning the steering-wheel) with ours.

4 FORCE FEEDBACK

In order to simulate the gearbox mechanical characteristics, we need to apply several forces on the user with the help of the Haptic WorkstationTM. But our first problem was to know which kind of forces should be applied on the user and overall how we could calculate them.

4.1 Approach based on the PID controller model

To know the forces we have to apply on the user, we decided to separate the cockpit space into small cubes in which a force is applied. To go from a position to another one, the hand must go through a lot of cubes. The applied force is different every time we change of cube. We decided to use a transfer function to compute the applied force when we go from a cube to another one. The main problem is that we can have a big difference of force between 2 contiguous cubes. We must quickly reach the new force to apply but we also have to avoid to apply a “step function” because we want to have smooth displacements and forces in order to make it more realistic.

We based our approach of the force calculation on the Proportional-Integrative-Derivative (PID) controller model (<http://www.expertune.com/tutor.html>). The force applied on the user arm depends thus on its position, but also on its speed and acceleration. As explained in [10], it is a good method to quickly change the applied force in a fuzzy way and without too abrupt changes which would lead to vibrations. We want to avoid them because it is not realistic in our simulation and moreover it can damage the Haptic WorkstationTM. We determined the coefficients of these 3 elements during the experiments.

Once this function defined, we must choose which forces we want to apply. We divide them into two groups: the static forces which depend on the position of the hand and the dynamic ones that also change with the movement direction. We will first present the “static” forces and conclude with the “dynamic ones” which are only used during the gear shifting.

4.2 Support forces

The support forces act on the vertical axis. The first support force we created is constant and act during all the simulation. It is used to compensate the weight of the exoskeleton such as described in [11]. It provides a kind of “one-gravity” to the user. It is very useful because during the simulation, it becomes quickly painful to carry the exoskeleton. Moreover it is really important for the user immersion that he/she does not feel the exoskeleton arm weight as discovered in [8].

The second kind of support force is used to simulate the lever. When the user leans his hand on the lever, it maintains his/her arm at the good height, preventing him/her to go through the lever. As explained in the previous subsection, this force is progressively (to avoid vibrations) applied in addition with the “one-gravity” force to reach a maximum value of 100N (due to the limitations of the Haptic Workstation™).

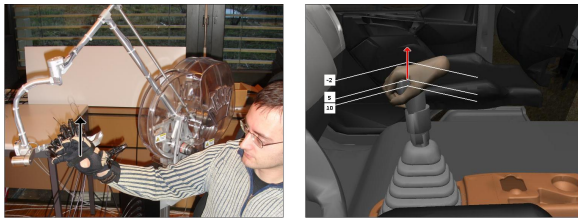


Figure 3: Support forces: (left) constant to compensate the exoskeleton weight and (right) dynamic to simulate the gearbox lever

4.3 Special added force

After the first tests we made, we noticed that people usually do not follow the lever trajectory. They indeed try to follow an horizontal translation instead of a circular movement (due to the rotation of the lever) while they are shifting the gears. This explains why their right shoulder hurt a bit after the simulation: they did not lean their hand on the virtual lever but tried to hold it on an upper level.

In order to oblige the user to follow the good trajectory and thus leaning his/her on the lever instead of holding his/her arm in the air, we add a supplementary vertical force. It is downward directed and acts as if the user hand was in a tube. He/she follows then the good trajectory and his/her shoulder does not hurt anymore. We will confirm it in the next section with the graphs provided by an EMG during the simulations.

4.4 Double-H forces

On the horizontal plan we will first apply the “Double-H” forces and then the “dynamic” forces provided by the RENAULT TRUCKS Cockpit Studies Department team (“dynamic”).

We first created the “Double-H” environment. As you can see here after, if the user strictly follows the double-lined segments, no static horizontal force is applied on him. But if he/she tries to go out of these segments, his/her movements are considered as forbidden movements by the program and the “Double-H” forces begin to act. These forces can be divided into three groups: when the lever is in the abutment (at the end of the segments), when it is in the transition axis (horizontal segment passing through the neutral point in the figure below) and in the vertical segments (between the gears and the transition axis).

You can see the centripetal forces that enter in action when the lever is in the gear abutment. In this case, the position variable in our transfer function equals the distance between the lever position and the center of the half-circle. If the user tries to go over the end of the

segment, the applied force will linearly vary from 0 to the maximal value (100N) to simulate a wall he/she should not go over.

You can also see other arrows on the transition axis and on the gear segments. They worked in an identical way as the first ones except that they are not directed to a central point but in direction of their orthogonal projection on the transition axis, respectively gear segment represented with a thick doubled-line.

Notice that the distance between e.g. the first and third gear is very small. We can then apply a maximal opposite force only on a few millimeters and the user can easily go over it and change of gear with no need to pass through the neutral point. We decided to implement a kind of state machine which allows the user to be detected in a gear only after passing through the transition axis. When the user comes into this space, he/she can be detected in another gear, otherwise he/she is always considered in the previous gear segment and a strong force push him/her to stay into it wherever he/she is.

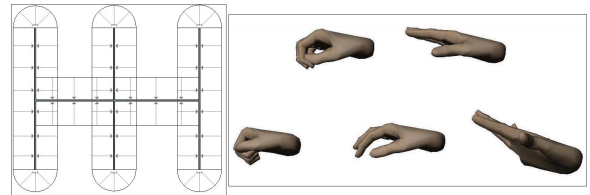


Figure 4: Double-H forces description and hand stored positions

4.5 Gear shifting forces

Finally the last applied forces, called “dynamic”, will be the “mechanical” ones corresponding to the gearbox values graciously provided by the RENAULT TRUCKS Cockpit Studies Department team. Note that these forces can be changed during the simulation via the 2D GUI we will present later.

As explained previously, their value changes depending on the direction of the user movement. We need thus to detect the shifting sense. In order to find it we always store the latest hand position of the user we get and compare it with the current. Unfortunately, even if the haptic thread which provides us the hand position is very fast (around 800 frames per second), the Haptic Workstation™ is so precise (1/1.000th of millimeter) that the user can never stay still (without movements). A dynamic force would then always be applied on the user who is always considered in movement. This force (in the opposite direction than the user movement in our case) would push him/her backward (if he/she goes forward), provoking a movement in the other direction (backward at this time) which would be detected by the program. A new opposite force would be applied in the other direction and this would continue infinitely, creating vibrations!

In order to solve this problem, we decided to create a value representing the accuracy degree we use to detect the direction of a movement. We set it by default at 0.3cm. The user must then have a displacement of more than 0.3 cm before the program detects he/she is moving in a direction. This distance can be easily reduced or increase, in real time with a slider on our GUI, depending on the user but with a tighten arm, people usually need this precision degree.

4.6 Pseudo-grasping forces

In order to make the user really think he/she is grasping a gearbox lever, we decided to use a pseudo-collision detection function depending on the angles value for each finger.

With the help of our own library and the Haptic Workstation™, we can get the current angle of every joint for each hand finger. We

initialize two positions at the beginning of the simulation: “hand opened” and “hand with the finger closed on the lever” and we store the sum of the angles for each finger in both positions. Indeed, to know the orientation of every phalanx, we get the angle value of the previous joint.

After this we get the current angles at every moment of the simulation and we compare their sum with the stored values (pictures of hand on the first line). While admitting that this sum is bigger when the hand is “closed” than when it is “opened” we can test them as described here after.

If these current values are bigger or equal to the values stored for the “closed on the lever” position (left picture on the second line), we detect that the hand is “closed”. A small grasping force is progressively and gently applied on the finger depending on the difference between the current sum and the stored one (this explain why in the third case, a null force may be applied - center picture on the second line).

If these current values are smaller or equal to the values stored of the “opened” position (right picture on the second line), we detect that the hand is opened. A “Delay state” is then applied and it suspends the simulation. No more force is applied.

Otherwise (center picture on the second line) the hand state (“opened” or “closed on the lever”) does not change. So if the previous state of the hand was “closed on the lever”, it does not change and a null force is applied on the finger because of the calculated difference between the current position angle values and the “closed” one.

4.7 2D GUIs in the application

In this application, as we must set a lot of parameters at the beginning and maybe during the simulation. We have thus developed some Graphical User Interfaces (GUIs) to allow the user to easily change them in real time.

At the beginning of the simulation, before we apply the forces due to the environment we have to set the Haptic Workstation™ and the hand displayed in the environment. To do this last one, we use our own library and prepare our hand in 4 steps with specific hand positions.

We can then set the main parameters of our simulation with the GUIs shown below: the “hand opened” and “hand closed” states, the location of the gearbox, the seat and the user point of view in the cockpit (right picture). We set the position while the hand is on the lever in the neutral point and the simulation can start. We also have some sliders to set the width of the gearbox segments, the gap between the 1st and the third gear and the distance we give to the user before we detect a movement.

During the simulation, we can at every moment (un)apply the “dynamic” and the special added forces which obliges the user to follow the gearbox lever trajectory. Obviously, all these operations are accomplished in real time and every value can be reset at every moment.

Finally we can set the “dynamic” forces during the simulation. As you can see here after in the central picture, depending on the Haptic Workstation™ limitations, we can apply a force of 100N (10kN) at the maximum. An example of possible forces we could apply on the gear shifting (from the neutral point to the 1st gear and back) is shown below.

5 COMFORT AND BELIEVABILITY

This section introduces two main aspects of our simulation: the user comfort and the believability of this application. We made some experiments to evaluate them with more than thirty people (seventy percent of males) between twenty and fifty years old. A few of them were used to work with haptic devices in virtual reality simulations.

5.1 Comfort

We first installed them in the Haptic Workstation™ to perform the experiment. After the simulation we asked them to define the shifting forces they felt. We began the simulation without the shifting forces to help the users to accommodate themselves to the application. We present here after a global average of the results we obtained.

To verify the user comfort during the simulation, we made some tests with the help of an EMG on the user. We wanted to verify how he used his muscles (biceps and deltoid) to compare the results obtained during the simulation with those we get in a real situation (while driving a real car). We decided to put an electrode on the

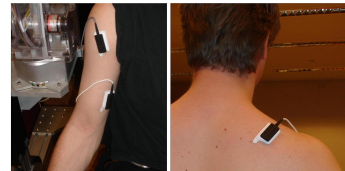


Figure 5: Location of the electrodes during the simulation

deltoid first to test the “gravity compensation force” developed in [11] and because we remarked the user shoulder even hurt after the first tests. You can see here after the results obtained by the EMG during the simulation without the special added force (on the top) and with it (on the bottom). Notice that we only used the “gravity compensation” and the “static” forces, i.e. without the forces due to the gear changes.

We used the special added force to oblige the user to follow the gearshift trajectory profit fully of the gravity compensation force. We can see that the use of the deltoid (channel B) is very smaller when we apply both forces. We then add the “dynamic” forces. Besides lines representing the biceps use (Channel A) is getting higher when the user is shifting a gear. As in the previous graphs, we applied both support and special forces on the right picture. Notice that at the end of the simulation with the compensation forces, the user tried to hold his hand a lot upper the gearbox lever.

At this moment of the tests (almost 5 minutes of simulation), we decided the user was enough accustomed to the simulation and we make disappear the “Double-H” segments which showed him/her the correct trajectories of the lever. These lines were very helpful at the beginning of the simulation but, a small moment after we erased them, the user could easily shift the gears. You can remark this adaptation time at the beginning of the graphs her after.

In fact the user fixed points are the neutral point and the transition axis. This explains why the user does not really need visual support to shift the gears after some training minutes. These places are indeed easy to find.

We finally compare the results obtained during the simulation with those we get while driving a real vehicle. Unfortunately, we did not have any truck for this last test. We decided to drive a car. This explains why the biceps use (during the gear shifting) is different from the results obtained during the simulation. But it seems to be quite realistic. You can notice that the deltoid does not work much more in our application than in the reality.

We can then conclude that we simulate a comfortable gear shifting.

5.2 Believability

The mandatory requirements to make our simulation believable are that the user should not perceive external embarrassments like graphical issues or vibrations which we will describe later in this part. We based our success criterion on the fidelity of the appli-

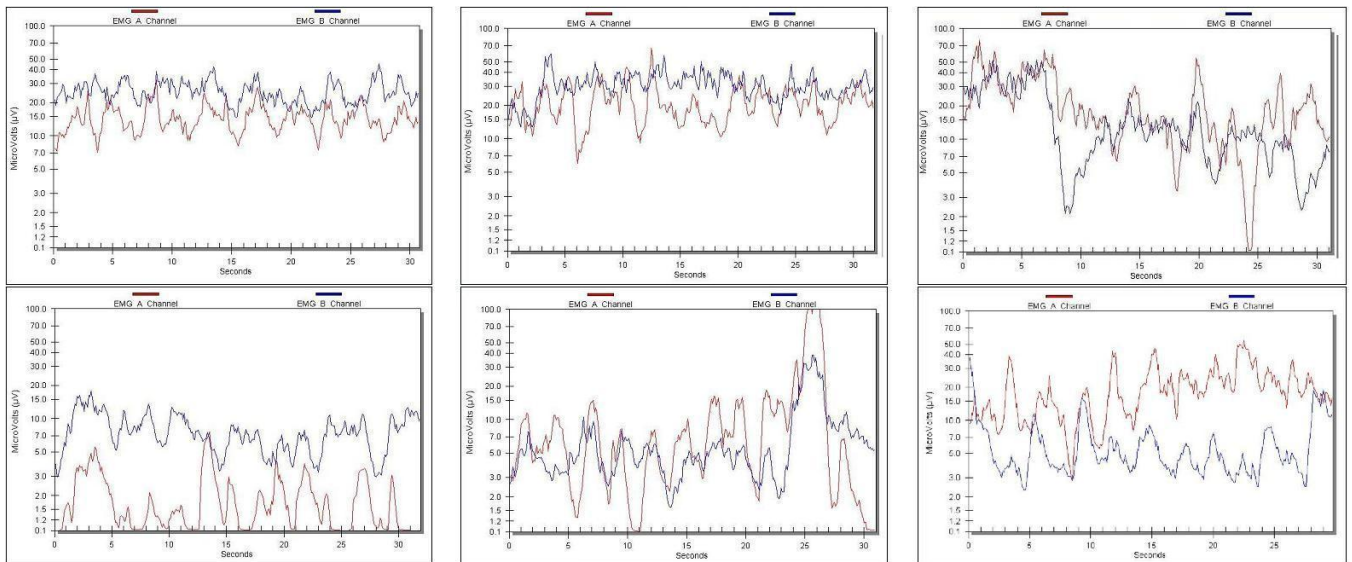


Figure 6: Top graphs represent the experiments without the special added force while bottom graphs use it (for left and center column). (Left) Results without gearshift forces, (center) with dynamic forces. (Right top) disappearance of the Double-H segments and (right bottom) results obtained in the reality.

cation in comparison with a real gearbox. Notice that due to the limitations of the Haptic WorkstationTM, we had to scale the applied forces to make the strongest force equals 100N. We need to provide some comfort to the user. As shown in the previous section, we got a sufficient comfort level in our application with the help of the gravity compensation force. It is also visible that he/she never had to apply a too big force during the simulation (except when he/she tried not to follow the gearbox lever trajectory).

As explained in [12], to make a believable simulation, we also need to provide forces as real as possible. We used the right forces needed to change the gears which were provided by the RENAULT TRUCKS Cockpit Studies Department. We are also working with the real distances of the gearbox segments, i.e. the gearbox lever movements.

In order to better immerse the user, we are working with a Head-Mounted DisplayTM combined with a Head-Tracker to get the orientation of his/her head. We use stereo vision at a frame rate between 40 and 50 frames per seconds which is good enough for the user.

The main possibility of “break in presence”, defined by M. Slater in [13], becomes from the vibrations generated by the Haptic WorkstationTM when the user reaches its limitations (e.g. with a tighten arm). We solved these problems by creating GUIs which allow to move the gearbox in the environment. But when we move the cockpit elements, we have to pay attention not too much moving them: if we put it too backward, the user elbow hits the station. We solved this problem by enlarging the Haptic WorkstationTM. Indeed, Immersion Corporation seemed not to have planned the situation we encountered but with our solution, the user arm does not hit anymore the station and we can then move back the gearbox in our simulation. We have almost no more vibrations and the believability is increased because the gearbox place in relation with the driver is more usual. Notice also that in contrary of VHD, the haptic feedback we apply does not depend on the environment. We do not need to test collisions by scanning the environment such as developed in [1] or to make some tests with the convex surfaces like in [2]. We made some tests to know more about the comfort of the user and his/her belief in the simulation as in [4]. At the

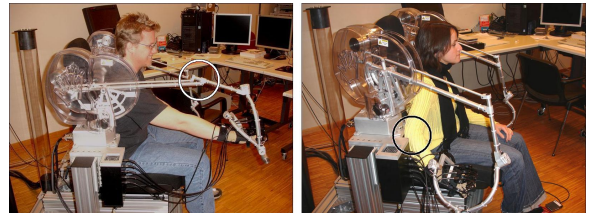


Figure 7: Limitations of the Haptic WorkstationTM

beginning of the simulation we only apply the “static” forces with a “Double-H” drawn to show to the user the way he has to use to get into the gears. We then add the “dynamic” forces.

The user can finely feel the lever with his fingers and we conclude the palm contact seems not to so be important. We did not implement some kinetic collision detection such as in [3]. We only stored at the beginning of the simulation the position of the hand while holding the lever and we get the angles of the fingers hand. We then only have to compare the current value of the angles with the stored one and decide if we have to apply a grasping force or not. We get an accurate enough information of the position of the finger end with no need to implement a real collision detection with the lever.

Moreover the “gravity-compensation force” helps a lot to make the simulation less painful. Unfortunately there is always a rotating problem with the wrist. The Haptic WorkstationTM tends to apply a rotation force to the outside on the user wrist. We could maybe compensate it with a small weight on the left side of the right hand exoskeleton. Otherwise the user intuitively finds the neutral point and “transition axis” even when there is no more the “double-H” lines on the gearbox lever to show the good trajectories to engage the gears. This is very important because this axis is usually the reference point for a driver. The user perceives very well the “Double-H” with his/her movements but sometimes he/she tries to hold the lever instead of following the good trajectory (rotation of the lever



Figure 8: Problem of an external rotating force due to the hardware

to go into a gear). We add a special vertical force to oblige him/her to follow the right way and the simulation is no more painful for his/her shoulder.

The dynamic forces are well sensed by the users. We always asked the users to draw the forces they felt during the gear changes. We then drew some possibility (here after on the picture) for the forces applied during the change of gear and ask him/her to choose the good one. Most of the time he/she finds the correct curve (left picture on the first line) or a similar one (right picture on the first line). We can conclude our system is accurate enough and close to the “scaled” reality. After some tests, we noticed that an adaptation

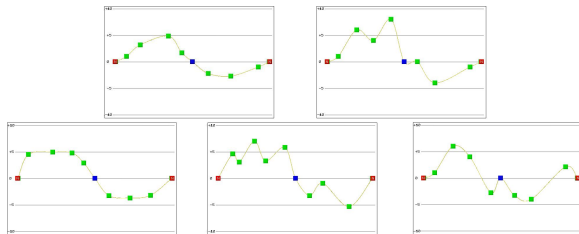


Figure 9: Schemata of the gear shifting forces proposed to the user

time around 5 to 10 minutes is mandatory. But then, the user gets very used with the application and enjoys it a lot. Moreover, with all the artifacts we used with the GUIs, we avoid all the vibrations due to the software and we have some ideas for those due to the hardware. We can thus say that this simulation is believable.

6 CONCLUSION AND FURTHER WORKS

In this article we had to show the possibility to have a comfortable and believable simulation of a virtual gear shifting with arm feedback. Our project is an application of the work presented in [11] in which a kind of “gravity-compensation” force was presented to improve the comfort during simulations with the Haptic WorkstationTM (two-arm exoskeleton).

We used biofeedback techniques with an EMG to measure the muscular activity of the arms while changing the gears with different forces: only the static or with the dynamic ones. We also made some tests in a real situation to compare the graphs and the obtained results were satisfying. Our application can then be considered as comfortable and believable after an adaptation time around 5 minutes. The forces to apply during the simulation are very close to the real one we had to scale because of the Haptic WorkstationTM limitations.

We could then use this application for driving lesson simulations with the haptic-feedbacked steering-wheel we develop as a new module in our application.

7 ACKNOWLEDGMENT

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