UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
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EMANUEL TERIBELE NOVAKOSKI

TG2: Simulating Haptic Impact in Immersive Systems

Work presented in partial fulfillment of the requirements for the degree of Bachelor in Computer Engineering

Advisor: Prof. Dr. Anderson Maciel

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UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
Reitor: Prof. Carlos André Bulhões Mendes
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Bibliotecária-chefe da Escola de Engenharia: Rosane Beatriz Allegretti Borges

ABSTRACT

In this work we explore the haptic pendulum, a device originally developed in our VIS (Visualization, Interaction and Simulation) Lab to generate sensation of holding different weights in VR. The goal of the present project was to redesign and assess the device as a means to provide force and mobility to VR haptics. It is known in the research community that force feedback device designs prioritize a grounded construction, where the ground offers an inertial support to be able to produce force. This is not ideal for VR where free motion is desirable. While previous works offer some alternatives by attaching devices to body parts or using propellers, none of them proposed a 2 degrees-of-freedom mass displacement handheld controller.

Our pendulum device consists of a mass that is driven by two servo motors on the surface of an imaginary hemisphere on top of the user's hand. The motors and mass construction is fixed upon a standard VR controller (HTC Vive) that is held by the user that interacts in the virtual environment. The pendulum was rewired from the original weight perception configuration to convey directional impulses instead of weights. While weights are stable forces towards the floor, directional impulses are instantaneous forces in controlled directions.

We then designed and conducted an experiment with users to assess how the impulse stimuli are perceived. We tested three dimensions for the system capabilities. The ability to convey different directions, different intensities and sequences of impulses.

Results show that directions can be identified, although not precisely, that the intensities tested are mostly well identified, and that sequences of impulses are correctly perceived even with sub-second time interval between impulses.

Keywords: Haptic interaction. Virtual Reality. Force feedback.

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

USB	Universal Serial Bus
VR	Virtual Reality
I/O	Input and Output

LIST OF ALGORITHMS

CONTENTS

1 INTRODUCTION

With the evolution and popularization of Virtual Reality (VR) and Augmented Reality (AR), scientists have searched for ways to artificially replicate sensations from the real world in the virtual world. Computers are able to create images and sounds with an impressive level of detail. The other senses (touch, taste and smell) have been explored more discretely. Among them, touch is the one receiving more interest from application developers. A whole scientific area, computer haptics, has developed to address the problem of producing meaningful and helpful touch and force feedback. One area where touch is arguably necessary is the one of virtual surgery simulators. Haptic feedback in surgery robots, for example, is believed to reduce errors in human-controlled robotic surgery (BETHEA et al., 2004). Beneficial effects are also seen on VR training of young surgeons, at the beginning stages of training. Another area is teleoperation and space exploration. Human control of rovers on rough surfaces have a positive effect of performance when the system possesses haptic force feedback, even when subject to transmission delays (SIEROTOWICZ et al., 2020). The human sense of touch is complex, however, and the use and the full benefits or haptic interfaces are still a topic of discussion.

While visual displays and audio devices evolved fast and are widespread due to high commercial demand, commonly found haptic devices are often limited and able to convey only simple stimuli, such as the vibration motors that are commonplace in smartphones. More complex haptic equipment are able to generate a force that constrain the user actions and may actively push and pull the user limbs and other body parts. This equipment tend to be expensive, tailored for each application and invariably require an anchoring point, which limits the user mobility. Another major limitation is the uneven nature of forces exerted by the interfaces (SREELAKSHMI; SUBASH, 2017).

We can classify the haptic interfaces in two groups: ground-based devices and body-based devices (SRINIVASAN; BASDOGAN, 1997). Ground based devices have a point of contact to a stable surface, such as a table. Body-based devices have no point of contact, and must be carried by the user.

In this paper, we propose an extension to a body-based haptic feedback device, the Haptic Pendulum (FURLANI, 2021). Our goal is to use this device to transmit the sensation of impact caused by the collision of a virtual object held by the player to other elements of a virtual world. In order to provide freedom of motion to the player, the device used must be body-based.

1.1 Objective

The objective of this work is to propose an implementation of haptic feedback in virtual objects in a VR environment. We are particularly interested in the sensation of impact.

We describe the sensation of impact as a directional force of short duration that acts on an object held by a player and provokes a feeling that the object is being pulled in the direction of the force. For example, a player holding a virtual shield would detect a movement when the shield is hit by a projectile.

For our modeling, we propose the following requirements:

1. The directional impulse detected by the user must be recognized as such;
2. The latency of the mechanical system must be low enough to allow the feedback to be used in conjunction with the visual stimulus;
3. The system must allow the user to differentiate stimulus of different intensities.

With this in mind, we have re-designed a weight-simulation haptic device in our lab with the purpose of generating forces in variable directions and intensities. Then, we conducted a set of experiments to assess the quality and accuracy of the stimuli perceived by human users.

1.2 Structure

After a brief review or previous works in chapter 2, we describe our haptic methods and implementation in chapter 3. In chapter 4 we present the evaluation protocol, and results and conclusions are respectively in chapters 5 and 6.

2 RELATED WORK

Haptic feedback is used in simulators as a way to increase realism. An example is Touch (3DSYSTEMS,), that uses motors to apply a reaction force to the hand of the user. Touch is represented in figure 2.1. This is classified as a ground-based device.

Figure 2.1 – Touch Device

Alternatively, there is the body-based classification, where the device has no support point. Examples include the DualSense controller, made by Sony (SONY, 2020), that uses haptic feedback in its vibration and trigger buttons. DualSense is represented in figure 2.2.

Figure 2.2 – DualSense Controller

Another example if the TorqueBAR (SWINDELLS ALEX UNDEN, 2003), in which a sliding mass shifts the center of mass of the device. TorqueBAR is represented in figure 2.3.

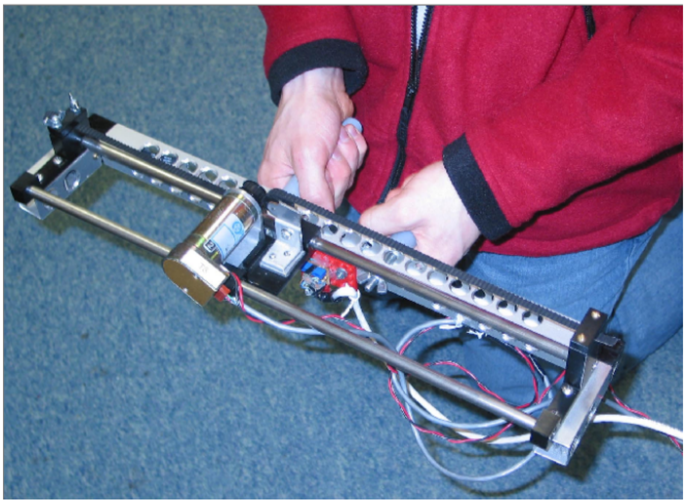


Figure 2.3 – TorqueBAR Device

Regarding software implementation in the field, we have a contribution made by (GEORGIOU et al., 2018): a rhythm game in VR featuring ultrasonic haptic feedback directly on the user’s hand, using the LEAP motion controller and an Ultrahaptics TOUCH Development Kit. It is represented in figure 2.4.

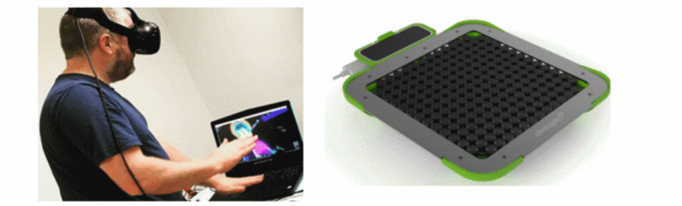


Figure 2.4 – Ultrahaptics TOUCH used in a rhythm game. Georgiou et al. (2018)

Another software featuring haptic feedback is the Haptic Battle Pong (MORRIS; JOSHI; SALISBURY, 2004). This game is based on the classic tennis games that became famous on the golden era of arcades. Battle pong implements haptic feedback in three degrees of freedom, by using a 3d Systems Touch, a ground-based device.

A different example of haptic feedback hardware was developed by Guinan et al. (2013): a video-game controller that features skin stretch haptic feedback on the thumbsticks. The device is shown in figure 2.5.

Figure 2.5 – Controller with skin stretch haptic feedback. Guinan et al. (2013)

In the field of prosthetics, we have a device designed by Battaglia et al. (2019). Its objective is to provide one degree of freedom feedback to users of prosthetic limbs. This device also utilizes skin stretch haptic feedback. It is represented in figure 2.6.

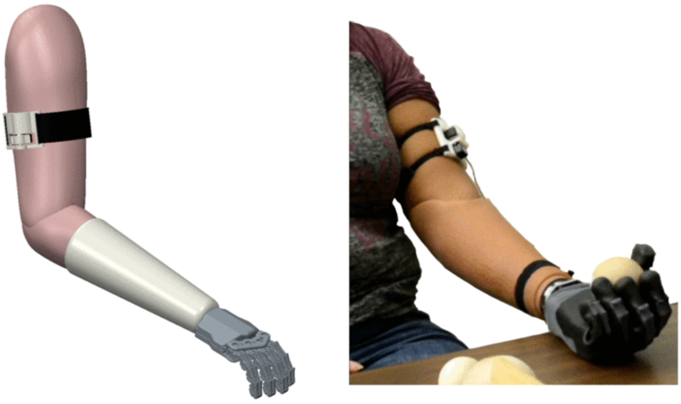


Figure 2.6 – Prosthesis with haptic feedback. Battaglia et al. (2019)

Finally, we have the Haptic Pendulum, illustrated by the figure 2.7. The Pendulum is a device designed to allow the user to feel the weight of virtual objects, and consists of a mobile mass attached to a rigid bar with two degrees of freedom, forming an inverted pendulum. The weight of the virtual object determines the angle of inclination of the pendulum, and its position in relation to the virtual hand determines a direction angle.

These angles control the position of the mass, limited by the upper hemisphere of a sphere. The mass constitutes a lever with the hand of the player. Its inclination determines the intensity of the effect sensed by the player. The perceived weight of the device is directly proportional to the inclination angle.

A side effect of this method is the inertia. Initiating and ceasing movement create an instantaneous force, undesired to the weight simulation. For our purpose of simulating instantaneous directional peaks of force this effect is very useful, as it allows the Pendulum to simulate apparent forces greater than its own weight. For this reason we have elected to use the Haptic Pendulum in our implementation.

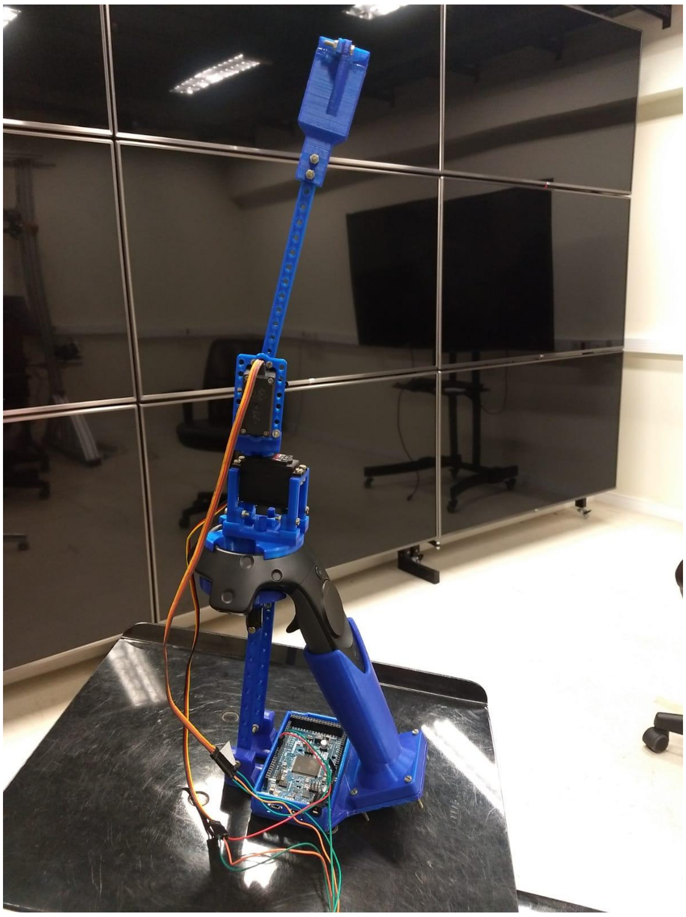


Figure 2.7 – Haptic Pendulum. Furlani (2021)

3 METHODS

3.1 Theoretical Foundations

Let P be a homogenous cylinder in rest, with geometric center C_r, height h and radius r, as represented by the figure 3.1. Its inertia tensor (WEISSTEIN, 1996) is:

$$J = \begin{bmatrix} \frac{1}{12}m_p(3r_p^2 + h_p^2) & 0 & 0 \\ 0 & \frac{1}{12}m_p(3r_p^2 + h_p^2) & 0 \\ 0 & 0 & \frac{1}{2}m_p r_p^2 \end{bmatrix} \tag{3.1}$$

The player is holding the object P. Therefore, the reference point for the rotation is the player's hand. We define this as the point C_r. The equation 3.2 defines a distance vector between the centers, $\vec{C}$.

$$\vec{C} = C_p - C_r \tag{3.2}$$

$$\vec{C} = \begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix}$$

The inertia tensor of a cylinder, relative to a point C_r can be defined by the Parallel Axis Theorem (ABDULGHANY, 2017), as shown by the equation 3.3, where δ_{ij} is the Kronecker delta (WEISSTEIN, 1999).

$$I_{ij} = J_{ij} + m(|\vec{C}|^2\delta_{ij} - C_iC_j), \tag{3.3}$$

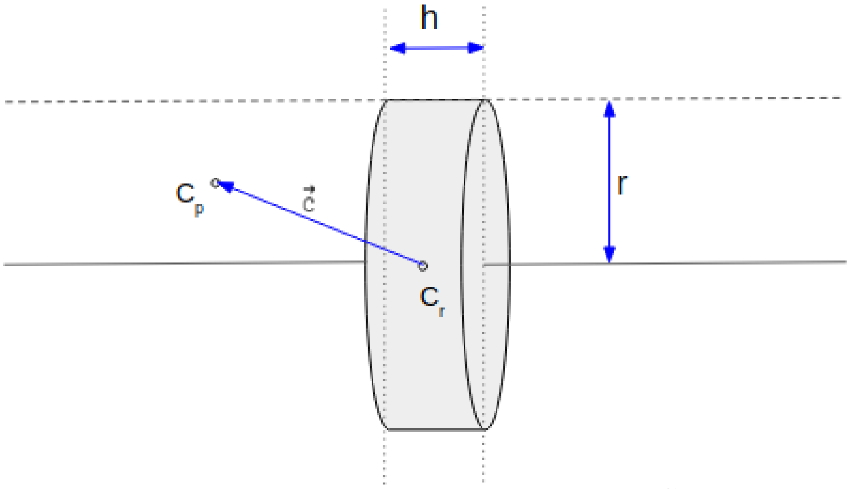


Figure 3.1 – Basic cylinder model with arbitrary center of rotation C_p and geometrical center C_r.

Let O be an arbitrary object of mass m_o, with velocity $\vec{v_o}$.

The objects O and P constitute the entire system, therefore, it is a closed system. Consequently, we observe conservation of angular momentum.

$$\Delta L = 0 \tag{3.4}$$

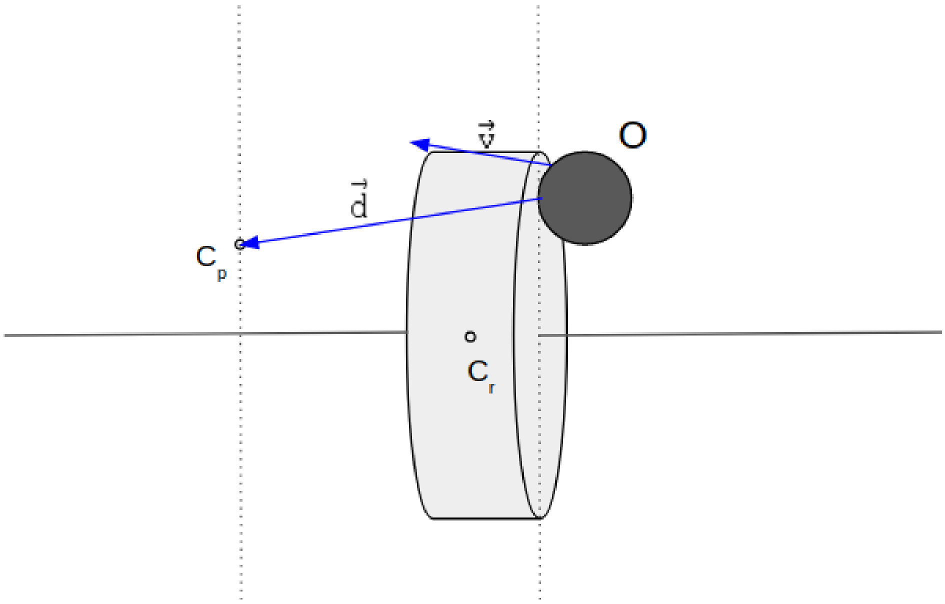


Figure 3.2 – Collision of cylinder with arbitrary object O

At a particular moment, O collides with P, as represented by the figure 3.2. Its energy is transmitted to P. We assume a perfectly elastic collision and disregard the linear movement. The object O comes to rest, while the object P rotates with angular velocity $\vec{\omega_p}$ around point C_p. The equation 3.4 becomes:

$$m_o \vec{d} \times \vec{v_{o1}} = I_p \vec{\omega_{p2}}, \tag{3.5}$$

where $\vec{d}$ is the distance between the center of rotation C_p and the collision point.

We are interested in the influence of the collision on object P, therefore, we can rewrite equation 3.5:

$$\vec{\omega_{p2}} = m_o I^{-1} \vec{d} \times \vec{v_{o1}} \tag{3.6}$$

The equation 3.6 determines the angular velocity of P after colliding, and will be used by the application to generate an impulse.

3.2 Implementation

The application was implemented within the Unity 3D game engine (UNITY, 2021).

The device used in the implementation is the Haptic Pendulum. It consists of a rigid arm, connected to two servos, one in the yaw axis and one in the pitch axis. These servos are controlled by an Arduino Due board, and communicate with the engine over serial interface (USB). Messages are passed as a string, containing a coordinate pair: the yaw and pitch angles. The data is converted into integers, and an Arduino library converts these into digital signals for the servos.

The objects in the scene are divided in two sets: the player objects and the application objects.

Each type of object consists of a script that extends the implementation of GameObject, Unity's basic object class. In Unity, the objects have multiple functional units called Components. A GameObject can have many components, including scripts. Given that a script cannot extend the functionality of a component, this application has a direct dependency of a RigidBody component.

3.2.1 Player Objects

The player objects are those in direct control of the player. The position and orientation of the player's hand is sourced from a VR controller and transformed into motion of the virtual set. The sets consists of a positional marker, that represents the point where the virtual hand of the player holds the system, and, by extension, represents its center of rotation, and a solid object of cylindrical shape, named a probe-object, representing a player held object, like a shield.

Unity's physics system has parameters for the mass and dimensions of an object. Given that the parameters are constant for each object during the execution, the I matrix, referenced by the equation 3.6, and by extension its inverse, can be calculated on startup and stored as a constant.

Player objects are limited to one instance per scene, given that they have direct access to the pendulum, and only one process can use the serial port that connects to the Arduino board.

3.2.2 Application Objects

The application objects are those under control of the application, independent of the player, controlled either by the physics engine or by programmed logic.

Like the Player objects, these also contain parameters for mass and velocity, and may contain a collision trigger to automatically call the impulse generation routine.

There is no direct communication between the application objects and the serial ports, which means the code for the application object is self contained in the GameObject. Therefore, there is no limit to the amount of Application object on a scene. There is, however, a limit to the amount of impulses the pendulum can be processing at a given time. The value of this limit is a subject of test in this work, as described in chapter 3.

3.2.3 Impulse Calculation

Each collision event is calculated as a directional impulse on the probe object, according to equation 3.6, and streamed to the pendulum mounted on the controller.

The resulting impact is translated into coordinates on the top hemisphere of a sphere and sent to an Arduino board that controls the pendulum.

3.2.4 Pendulum Movement

The pendulum is capable of positioning the weight in any point of the top hemisphere of a sphere. Its horizontal distance from the base determines the intensity of the force.

The pendulum's servos have a range of 180º, so, to move the mass beyond this point, we must position it in the reflected direction across the center and pitch it in the opposite direction.

This is represented in figure 3.3. In order to position the mass in the left side of the pendulum, we must position it in the right side and invert the pitch direction.

The initial position of the pendulum is vertical, where the horizontal distance is zero, and therefore, the force sensation is minimal. The application triggers a collision between the objects and calls the routine described in section 3.1. The velocity is converted into coordinates and streamed to the device, that positions the weight at the coordinates.

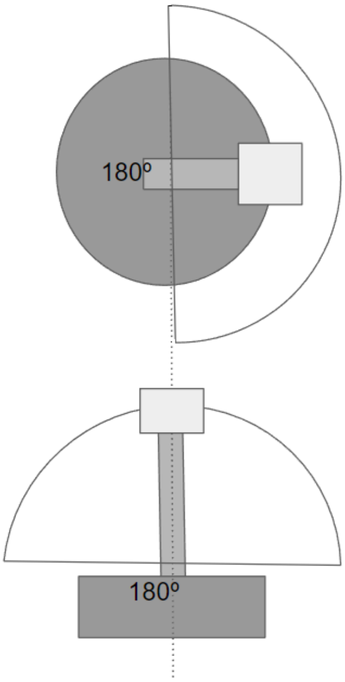


Figure 3.3 – Range of movement for the servos

The length of the arc is calculated based on the intensity of the effect. It must be noted that the motors have inertia, and its speed should be set in a way that the force in the opposite direction is minimized.

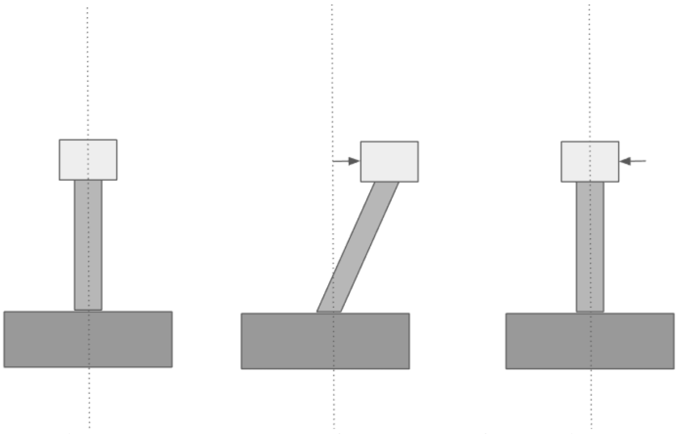


Figure 3.4 – Sequence of movement for one impact

As soon as the motors reach the final position, they stop, allowing the player to experience its inertia, and begin moving in the opposite direction, back to the vertical position, increasing the feeling of inertia. The device is now ready to receive the next impact. This flow is represented in figure 3.4

4 EXPERIMENTS

Our system is able to move the device's pendulum to the respective angles computed from collisions in a simulated virtual environment. The velocities and geometry of colliding objects are accounted for. However, as the pendulum design demands two opposite accelerations for each impact, one in preparation and another in response, it is difficult to predict how users will perceive and discriminate impacts. Moreover, some angles may impose more latency than others, and the latency between impacts may limit the frequency of impacts that can be perceived.

To gather information about how these features impact the use of the system, we propose here an experimental assessment with a population of volunteer participants. The experiment consists of three sequential tests: the direction test, the intensity test, and the counting test.

During the tests, the users will be wearing a head-mounted display (HMD) and headphones to prevent the use of sight and hearing in the discrimination tasks.

Each participant receives a unique ID when filling out a pre-test form, calculated as the addition of the test's actual index and the value 480 (e.g. the first volunteer receives the ID 481, the second receives the ID 482, and so on).

Independent variables and other constant parameters will be detailed in the description of each test further below in this chapter. We anticipate, however, that these values are predefined and stored prior to the experiment to be later passed as parameters for the tests. They are uniformly distributed along the values ranges. The combinations are generated, their order is randomized, and they are saved to a CSV file. Each combination of parameters is experienced twice on every user-session instance.

During the test, for each subject, the system imports the respective CSV file and stores it in an array. The array is rearranged, following a latin square (WALLIS; GEORGE, 1997) with index determined by the unique ID.

The volunteer is instructed to put on the HMD and headphones, and receives the pendulum mounted on the controller to their dominant hand. A virtual wall is presented, which contains instructions about the experiment and a counter that measures progress. The volunteer interacts by moving and pressing the trigger button on the controller.

After pressing the button to start, the system applies a stimulus to the pendulum, and the user must point the controller and press the trigger to register an answer. Each test implements its own logic of measure, as detailed in the respective sections below. The recorded measure is stored in the array, forming a tuple with the actual value read from the input file. At the end of the experiment, the array and the user ID is saved into an output CSV file.

A representation of the flow, in pseudo-code, is described in algorithm 1.

Algorithm 1 Basic flow for all tests

```
Require: parameter file is present and Arduino is connected via serial interface
connect to Arduino
let $a$ be an array with the parameters
rearrange a as a row of a latin square, based on user ID
print instructions on screen
while user has not pressed button do
    wait
end while
for each test in $a$ do
    apply impulse
    while user has not pressed button do
        wait
    end while
    capture user response
    update progress counter
end for
save results in output file
if there is another experiment then
    load next experiment
else
    print end message
end if
```

The participant's position and orientation is determined by the HMD, and the hand position and orientation is determined by the controller.

During every experiment, the virtual object being held by the player is the same: a cylinder with 1 meter of diameter and 0.1 meters of height, with contact point located 0.1 meters from the center of mass, along the symmetry axis. It is represented in figure 4.1 The object is meant to represent a round shield.

After concluding the three tests, the participant fills a second form, answering questions about their confidence level in each experiment, as well as reporting muscular pain and fatigue, headaches and nausea. A copy of the forms can be found on the Appendix section.

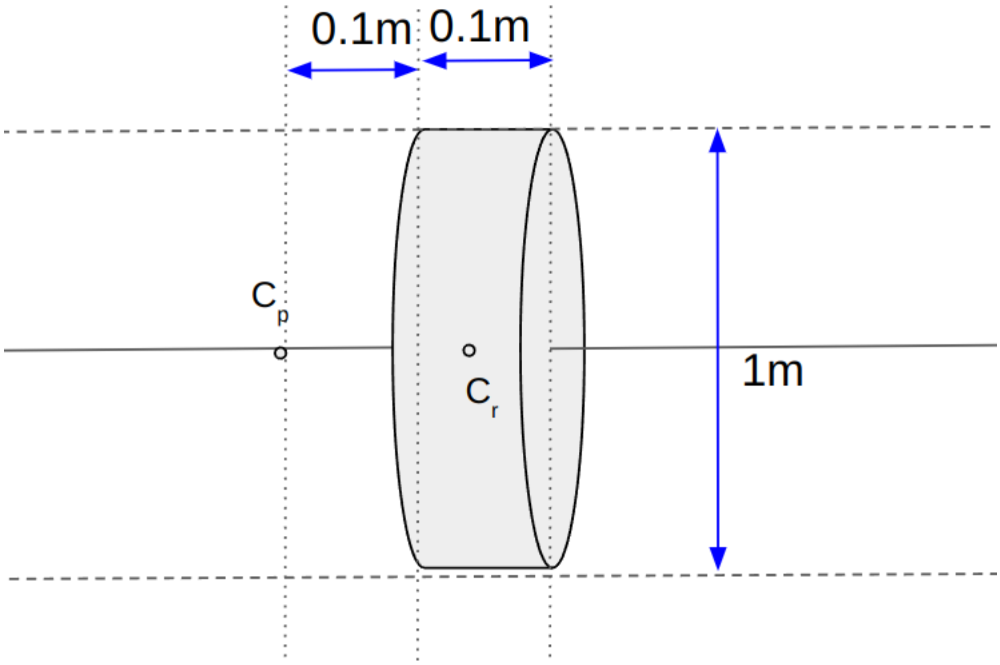


Figure 4.1 – Virtual shield held by the player

4.1 Direction Test

This experiment's objective is to determine if the impulse of the pendulum can be perceived as a directional stimulus. We aim to test the following hypotheses:

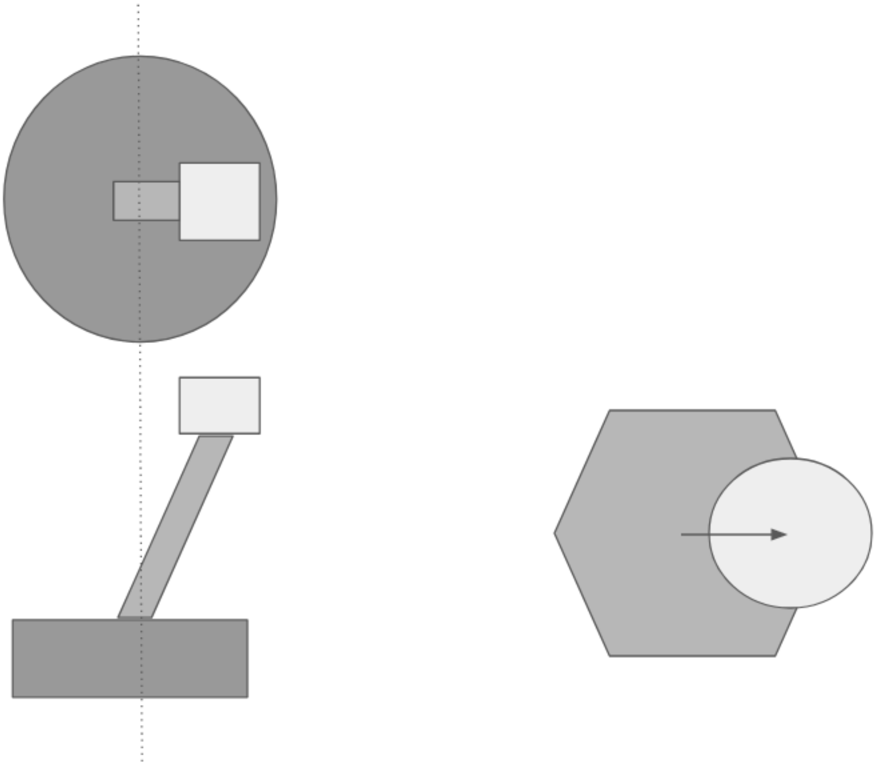
H1.1 Users are able to identify the direction of the stimulus;

H1.2 The ability to identify the direction of the stimulus is independent of the angle ;

There is only one independent variable for this test: the angle around the vertical axis, here named α, measured with the global north as a reference. There is a constant, the mass m of the impacted projectile that metaphorically causes the impact torque. This constant is set to the value of the maximum mass allowed by the system. As such, a test instance is determined by the set $\{\alpha, m_o\}$.

The experiment consists of 12 different values for α, spread in intervals of 30º. Since we are interested in testing the perceived direction of the stimulus, the mass is constant.

The test starts with a short explanation shown on a virtual wall in front of the participant. When the participant is ready, they can press the button and start the first impact. The pendulum lines up to the direction determined by the test iteration and pitches the mass until it reaches the maximum inclination. It then returns to the upright position.



(a) Pendulum Movement. Top and lateral view. (b) Indicated direction. Top view.

Figure 4.2 – Pendulum Movement and expected response from user

The participant is prompted to point the controller in the direction they perceived the impulse and press the button. The vector from the position of the participant's head to the position of the player's hand is calculated, and the angle between this vector and the global north is stored in the tuple of the experiment instance.

The participant is now prompted to realign their body with the global north and press the button again. If this is the final instance of the test, it loads the next test. If it is not, this triggers the next instance of the current test.

The pseudo-code representing this flow is show in algorithm 2. Operations such as interface initialization are omitted from this section, as it is described in algorithm 1. Figure 4.2 illustrates the process.

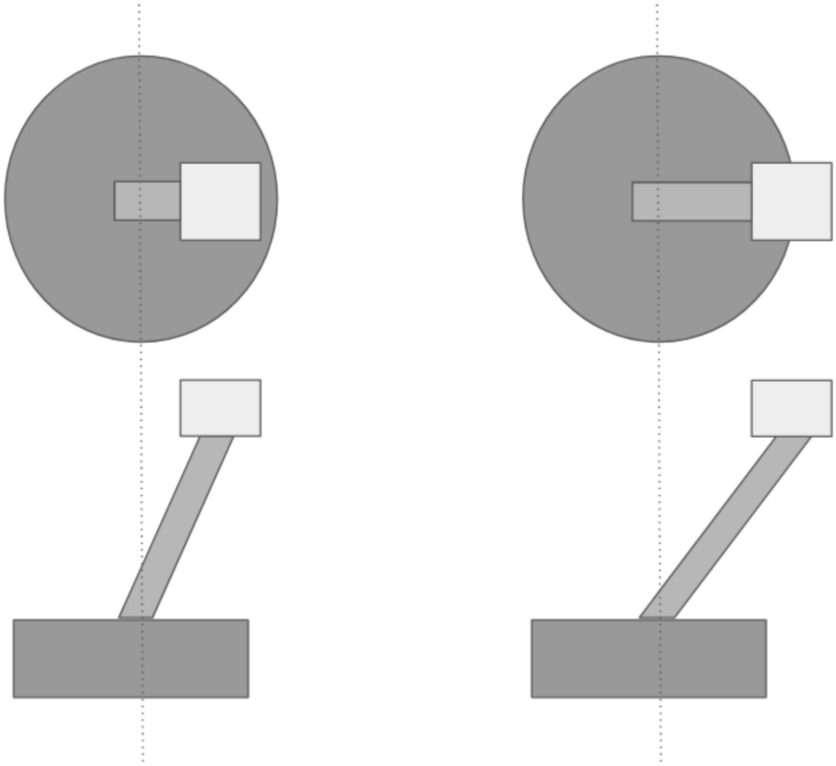
Performance is measured as the deviation degrees from the actual impulse angle. The best possible case is 0º of deviation, and the worst is 180º.

4.2 Intensity Test

The objective of this experiment is to determine how users perceive different intensities of impact. We aim to test the following hypotheses:

Algorithm 2 Procedures for direction experiment

```
Require: element of array of parameters a[i], mass of colliding object $m$
Ensure: $m \leq m_o$
procedure GENERATE IMPULSE
    let f be the intensity as a proportion of max pitch, based on equation 3.6 and a reference mass $m_o$
    if a[i].alpha > 180 then
        a[i].alpha ← a[i].alpha - 180
        f ← -f
    end if
    set pendulum yaw to $\alpha$, set pendulum pitch to 90º
    while pendulum is moving do
        wait
    end while
    set pendulum pitch to (90+(f * 90))
    while pendulum is moving do
        wait
    end while
    set pendulum pitch to 90º
    while pendulum is moving do
        wait
    end while
end procedure
procedure COLLECT USER RESPONSE
    let p be the position of the HMD and h the position of the controller
    let nv be the global north vector
    let ph be the vector from p to h
    a[i].measure ← angle between np and ph
end procedure
```



(a) Low intensity impact (b) High intensity impact

Figure 4.3 – Different pendulum movement for different intensities

H2.1 Users are able to identify different intensities;

H2.2 The ability to identify different intensities is lower at certain angles;

There are two parameters, or independent variables, in this test: a mass m, and an angle α around the vertical axis. There is a constant, the reference mass, here named m_o. For the angle α we have chosen four values: 0º, 90º, 180º and 270º. For the mass we have chosen the values 1 kg, 2 kg and 4 kg. The experiment consists of 24 combinations of mass and angle. For every combination we observe the following property:

$$m \neq m_o$$

The value selected for the reference mass, m_o, is the following:

$$m_o = 3.5kg$$

Similarly to the direction test, here the user receives a short textual explanation on a virtual wall. When the participant is ready, they can press the button, which triggers a sequence of two impacts separated by a delay of 600 ms. Both impacts are done in the same direction, determined by α, but a different mass is applied in each of them. As such, a test instance is determined by the set $\{m, \alpha, m_o\}$, as one of the masses is always the reference.

The time elapsed between impacts is such that an observer could perceive an interval where the pendulum is static.

After sensing both impacts, the user must answer if they perceived the second impact as more intense than the first. The possible answers are "yes" and "no". Every volunteer receives a permutation of the same set of experiments, following a latin square. The answer is recorded, and the level proceeds to the next impact or loads the next experiment.

Performance for this test is measured as whether the volunteer answered the question correctly. General confidence in these answers is measured only at the post-experiment form.

The pseudo-code representing the sequence of steps for this test is shown is algorithm 3. Base operations are omitted for the sake of conciseness.

4.3 Count Test

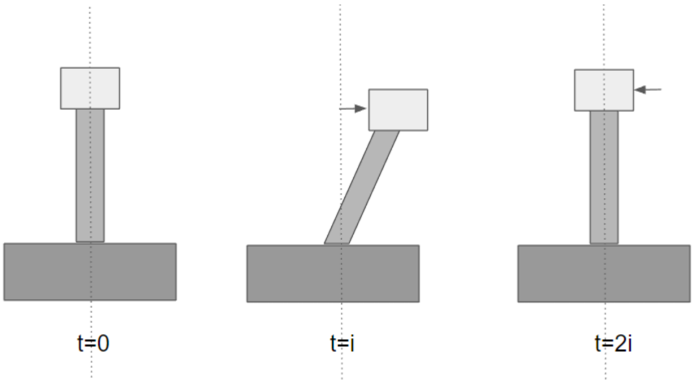


Figure 4.4 – Pendulum motion for an impact. The acceleration of the return motion is twice the acceleration of the forward motion.

The goal of this test is to determine the delay time necessary between two impacts to allow them to be individually perceived by the user. We propose the following hypothesis:

H3.1 The elapsed time between impacts affects the user ability to identify the number of impacts in a sequence;

There are two parameters (independent variables) for this test: a number n of

Algorithm 3 Procedures for intensity experiment

```
Require: element of array of parameters a[i], reference mass $m_o$
procedure GENERATE IMPULSE
    let $f_1$ be the intensity of the impact of the first mass, and $f_2$ the intensity of the impact of the second mass, based on equation 3.6
    for each impact do
        if a[i].alpha > 180 then
            a[i].alpha ← a[i].alpha - 180
            f ← -f
        end if
        set pendulum yaw to $\alpha$, set pendulum pitch to 90º
        while pendulum is moving do
            wait
        end while
        set pendulum pitch to (90+($f_1$ * 90))
        while pendulum is moving do
            wait
        end while
        set pendulum pitch to (90+($f_2$ * 90))
        while pendulum is moving do
            wait
        end while
        set pendulum pitch to 90º
        while pendulum is moving do
            wait
        end while
    end for
end procedure
procedure COLLECT USER RESPONSE
    let h be the position of the controller
    if h is within bounding box of button "Yes" then
        a[i].answer ← 1
    else if h is within bounding box of button "No" then
        a[i].answer ← 2
    end if
end procedure
```

impulses in a sequence, and a time interval t between each impulse. Due to limitations of the hardware i/o, t must be larger than 600 ms. There is a constant, the mass, m, valued as the maximum mass allowed by the system. The experiment consists of 24 combinations of n and t values.

Once again the user receives instructions on the virtual wall. Pressing the button triggers the first impact. After t milliseconds of delay, the system triggers another impact, and so on, up to the quantity defined by n. As such, a test instance is determined by the set i, t, m.

After the last impact, the player is prompted to answer how many impacts they felt. The possible answers are the numbers between one and three, inclusively. The answer is recorded, and the experiment proceeds to the next instance if it exists, or displays a "thank you" message on the wall. The volunteer has now finished testing.

It is important to note that, even when there is only one impact in the instance, the experiment will wait for as long as three impacts would take (3 times t), so that the participant can not attempt to guess the answer based on how long the prompt takes to appear. This is implemented by triggering the wait routine without triggering the pendulum movement routine.

The flow is documented in algorithm 4. Figure 4.4 represents the flow of each experiment.

Like the second test, performance is measured as whether the volunteer answered the question correctly. Confidence in this answer is also measured at the post-experiment form.

Algorithm 4 Procedures for count experiment

```
Require: element of array of parameters a[i], mass $m$
procedure GENERATE IMPULSE
    let $f$ be the intensity of the impact of mass $m$
    for three times do
        set pendulum yaw to 0º, set pendulum pitch to 90º
        while pendulum is moving do
            wait
        end while
        if impact count < $n$ then
            set pendulum pitch to (90+($f$ * 90))
            while pendulum is moving do
                wait
            end while
            set pendulum pitch to 90º
            while pendulum is moving do
                wait
            end while
        end if
        wait i seconds
    end for
end procedure
procedure COLLECT USER RESPONSE
    let h be the position of the controller
    if h is within bounding box of button "1" then
        a[i].answer ← 1
    else if h is within bounding box of button "2" then
        a[i].answer ← 2
    else if h is within bounding box of button "3" then
        a[i].answer ← 3
    end if
end procedure
```

5 RESULTS

In this chapter we present the results obtained and discuss them in regard to the initial hypotheses.

We recruited 4 volunteers from the university community to participate in the experiment. They were aged between 23 and 28 years, and were 3 male and 1 female. All volunteers were right-handed and have no motor limitations. One reported short-sightedness.

5.1 Direction Test

In this test we evaluated the ability of the system to convey a directional stimulus. Volunteers pointed the direction they have sensed upon the impact. We have measured the difference between the reported angle and the actual angle. Analyzing all the responses, we observe an average error of 65º, with standart deviation of approximately 22,13º. As a low pointing accuracy is expected with the free hand, it is meaningful to consider an acceptable margin for the responses around the impact angle. We grouped them by errors within 30º around the target. Results can be seen in figure 5.1.

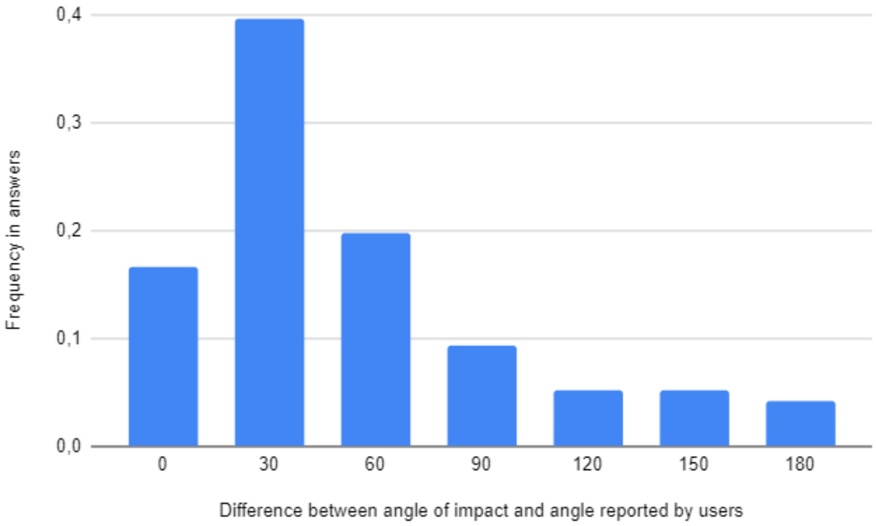


Figure 5.1 – Frequency graph for answer divergence on first test

We have also measured the proportion of correct answers per direction, considering the input angle α. The results can be seen in figure 5.2. We have noticed a substantial difference in proportion along direction, suggesting validity of hypothesis H1.2. In particular, the 330º mark had the lowest proportion of correct answers. Additionally, the 180º and 210º directions had the largest proportion of inverted answers. The 180º mark had no correct answers, only inverted. Finally, the average errors per direction in degrees are represented in figure 5.3. Their high variability also supports validity of hypothesis H1.2.

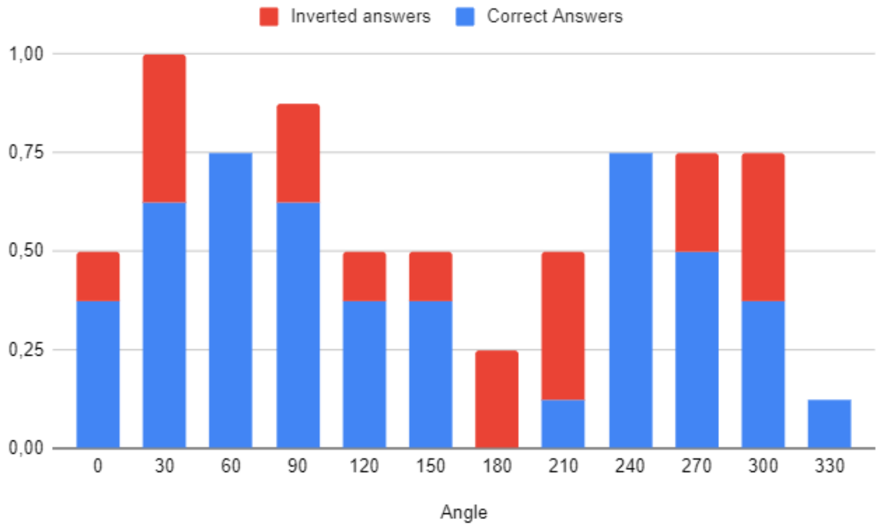


Figure 5.2 – Proportion of correct answers in relation to angle α

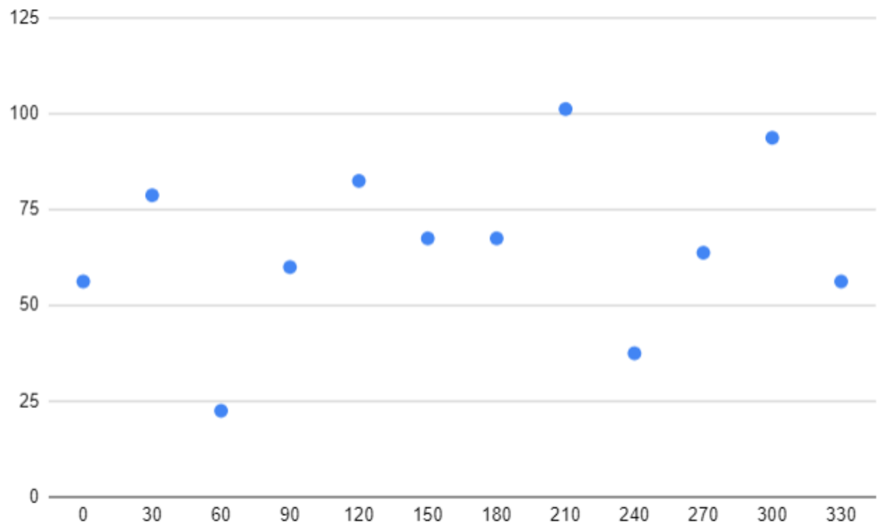


Figure 5.3 – Average error in relation to angle α

As already mentioned, if we consider a margin of error of 30º, the smallest difference between two actual impacts in our test, we can determine a rate of reasonably correct responses. Based on that, the participants have answered correctly 45.83% of the tests. However, as we know that the inertia of the mass moving in the opposite direction for preparation would create a smaller anticipated impulse, we can argue that this impulse may be confused with the actual impact. In this case, it is justifiable to consider that although the symmetric direction was pointed, the direction, and nothing else, is the main factor. When we consider the pendulum moving in the opposite direction, with the same margin of error, we would have an additional 15.28% of correctly pointed directions. This is illustrated by figure 5.4. We have asked our volunteers in our form if they considered that many impacts had the same direction, to which two answered yes.

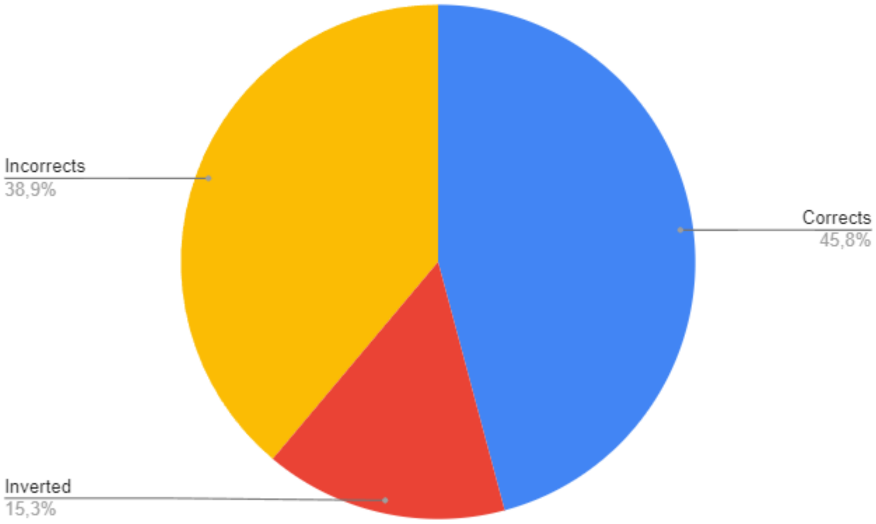


Figure 5.4 – Proportion of correct and inverted answers

Considering that, theoretically, a participant would be expected to answer 16.6% of the questions correctly if they guessed every answer, we obtained almost three times this value, a substantial increase in proportion, favoring hypothesis H1.1. We consider these results as a small success for the device tested in terms of direction.

5.2 Intensity Test

In this test we evaluated the ability of the system to convey impacts of different intensity. We have measured the perception of impacts of different masses in relation to a fixed mass of reference. Results can be seen in figure 5.5.

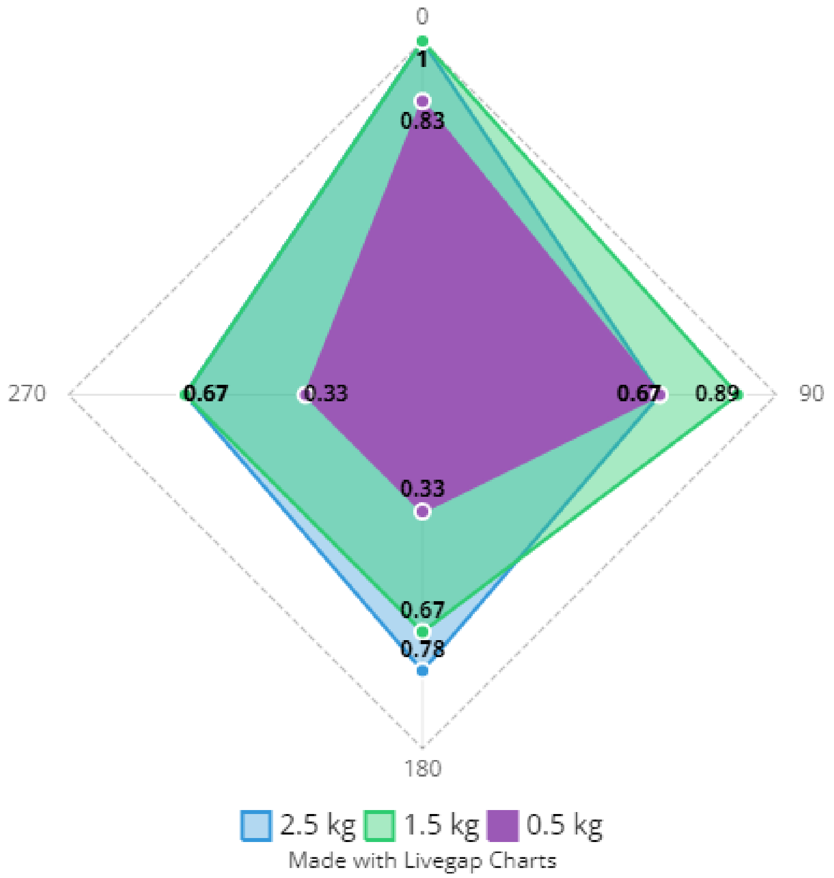


Figure 5.5 – Rate of correct responses based on angle and weight difference

A representation of the relation between correct answers and the weight difference is in figure 5.6. We can see the proportion of correct answers increasing with the difference in weight, as expected, but platooning around the 1.5kg difference. The standard deviation was 14,5%.

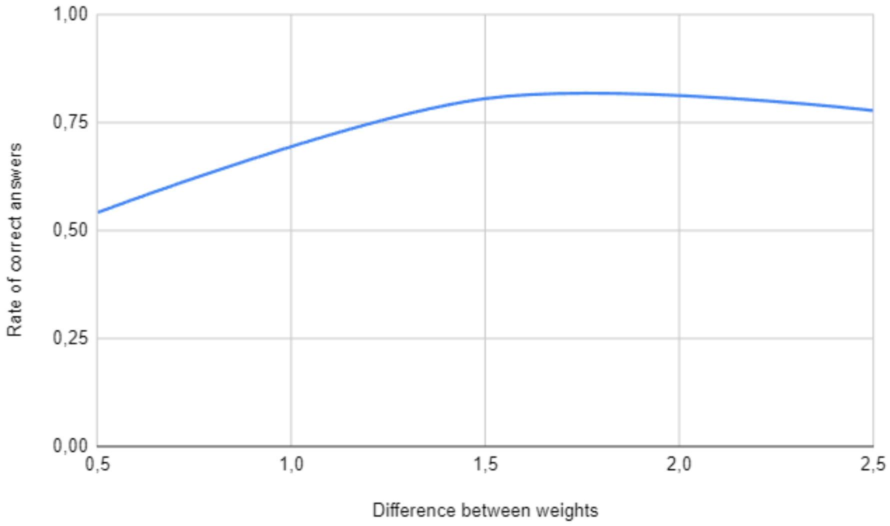


Figure 5.6 – Correct answers based on weight difference

In the post-experiment form, some volunteers reported that they felt both impacts in equal intensities for most of the experiments, while some reported that the intensities were different in all experiments.

As a total, our volunteers have answered correctly 75% of the instances. This is represented in figure 5.7. This and the results of figure 5.5 favor the hypotheses H2.1 and H2.2, respectively. As such, the device demonstrates capability to convey different intensities.

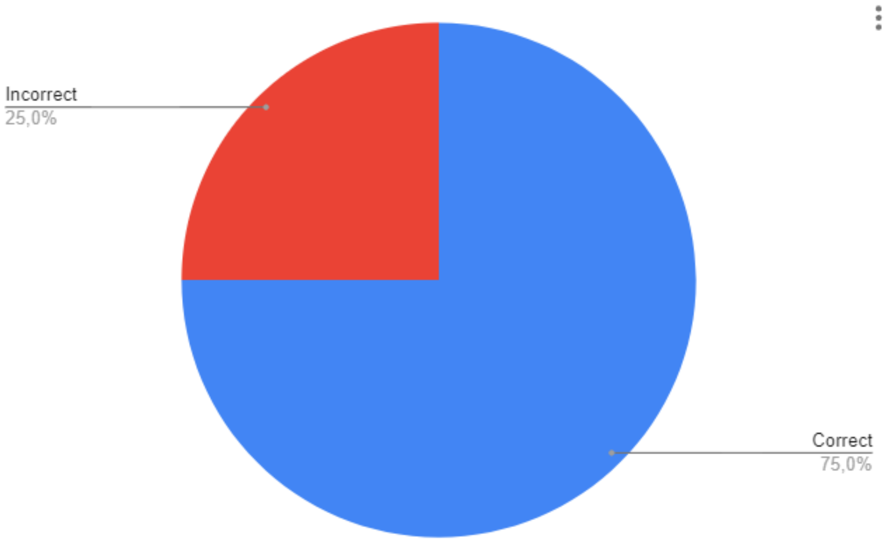


Figure 5.7 – Proportion of correct answers on intensity test

5.3 Count Test

In this test we evaluated how the interval between each pendulum movement affects perception of the number of impacts in a short sequence. We measured the perception of impacts with different time intervals elapsed between them. Although the goal is not to maximize the number of correct responses, we depict the overall responses in figure 5.8 for reference.

During the tests, we noticed that some volunteers reported twice as many impacts for a considerable amount of instances, even when presented with only three possible answers. This suggests that the volunteers were sensing the forward and the return motion of the pendulum as two different impacts, as suggested by the results of the direction test.

During this test, every volunteer asked if they should consider both motions as a single impact. This shows that they are aware of the double acceleration but understand each pair correspond to one actual impact. They were told to answer the amount they

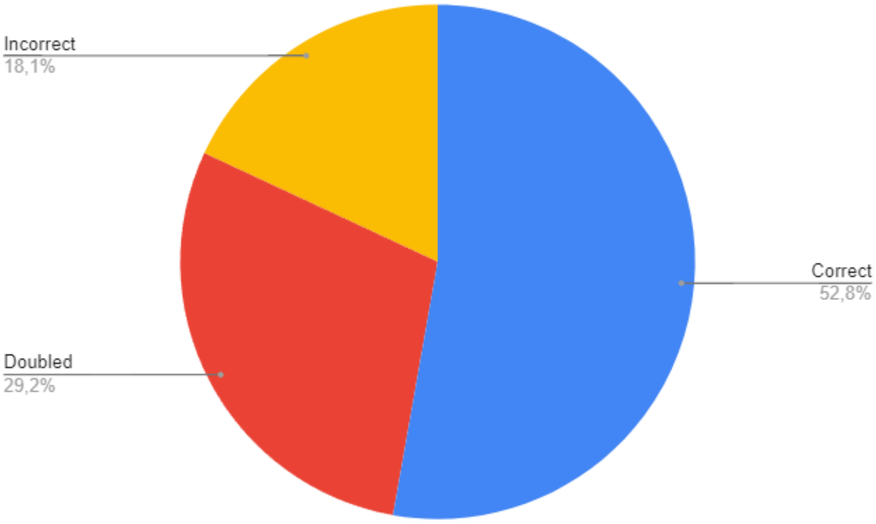


Figure 5.8 – Proportion of correct answers on third test. Doubled counts refer to when participants count the pre-impact and the real-impact accelerations as two impacts instead of one.

understand as one impact, in such a way that a minor acceleration should be considered part of the impulse represented by the larger acceleration instead of a separated impulse.

This test has a correct answer rate of 52.8%, while the doubled answers were present in 29.2% of the experiments.

The relations between the number of impacts and proportion of correct responses can be seen in figure 5.9. These results show very little variance.

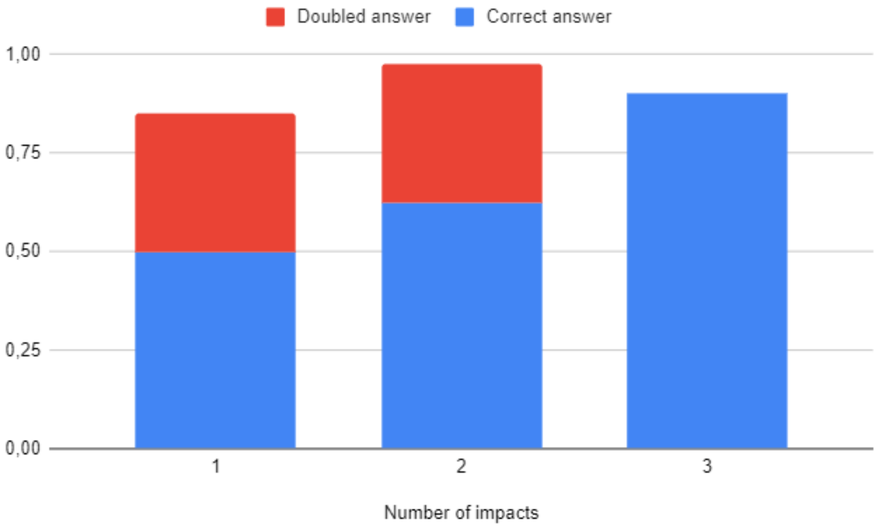


Figure 5.9 – Proportion of correct answers in relation to number of impacts

Most importantly, the relation between the time interval and correct counts is represented in figure 5.10. These results show a considerable increase in correct answers as the interval grows, achieving perfect score at the 1 second mark. This suggests hypothesis H3.1 is valid. Although we did not test longer intervals, we can assume that above 1 second each individual impact is perceived. For intervals shorter than 0.6s, we need to improve the device's design, as our I/O buffer is not able to hold them, before new experiments can be conducted.

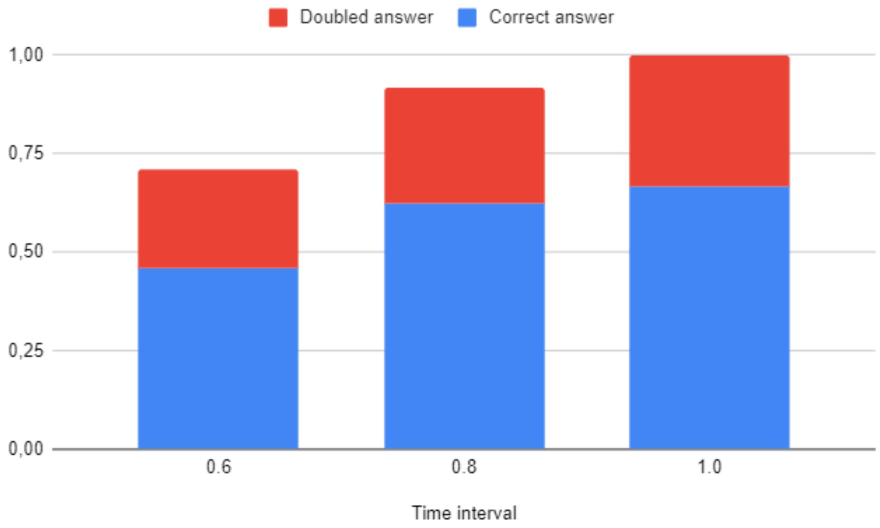


Figure 5.10 – Proportion of correct answers in relation to time interval

An interesting result in this test is that the first few iterations had a higher error rate. Figure 5.11 represents this result. This suggests that the volunteers required a few impacts to get used to the pendulum. It is a very steep learning curve, however.

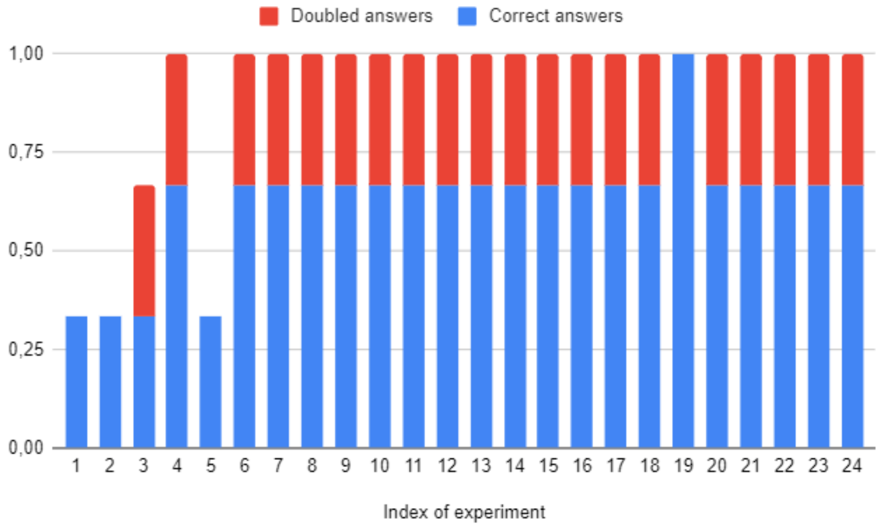


Figure 5.11 – Proportion of correct answers in relation to experiment order

In the post-experiment form, when asked how many correct answers they believed they had on this experiment, one volunteer reported belief in all answers correct, while the others reported belief in most of them correct.

5.4 Limitations of current model

Considering that the pendulum has two degrees of freedom, while objects in VR have six, we know by design that the pendulum cannot represent every form of impact.

It is important to note that during the tests a 3D printed part from the pendulum ruptured. This part is a disk that connects the lower motor to the upper motor, and is the only point of contact between the two parts that form the body of the device. As a consequence, this part must hold the entire force issued by the movement. This stress was too high for the plastic used in printing, and had to be replaced during the experiments. A possible solution to this issue would be to manufacture this piece in a material that can handle the stress, such as metal.

6 CONCLUSION

In this work we have presented an extension to the Haptic Pendulum, a programmable body-based haptic feedback device. Our extension makes use of the pendulum interface to convey a sensation that a virtual object in the hands of a user is colliding with another solid object.

Our implementation was made in Unity game engine, using the physics components contained in it to trigger pulses on the device based on physical information from the engine and a calculation of energy transmission through elastic collision.

We have designed three test levels to determine the device's capability of conveying a directional impulse, conveying impulses of different intensities, and rendering the impulses at different time intervals between impacts. The stimuli were provided to a population of users and responses were collected for analysis.

Regarding the direction test, we have seen a substantial increase in correct answers when compared to pure randomness. However we have noticed a substantial amount of inverted answers, due to the inertia of the device pushing the hand of the player in the opposite direction when preparing for the actual impact. The results were 45.83% for correct answers with a margin of 30º. When adding the 15.28% correct answers for inverted direction, this total increase to almost 60% (59.11%). We attribute a considerable part of the effect on incorrect responses to an inaccuracy in our method to compute the angle pointed by the participants in response to the stimulus. This pointed direction is computed as the vector passing from the head position to the hand position (both tracked by the system).This is inaccurate as the actual pointing direction should arguably use a vector departing from the shoulder. This causes a global error and, as the participants are all right-handed, there is also an increased bias when pointing to the left. The low score for the 330º direction is an important evidence of that issue.

Regarding the intensity test, we have seen the correct answers amounting to 75% of the total. Higher differences in mass resulted in a higher proportion of correct answers. Further studies should focus on a larger number of different masses, which would also provide smaller mass differences to test for finer accuracy. The current device can provide more variety for the inclination angle, which is one way to represent heavier masses. Another way is to better control the speed or acceleration of the pendulum, which the current design with 180º servo motors is unable to provide.

Regarding the counting test, we have seen the correct answers amounting to 52.8%

of the total, and over 80% of answers with doubled impacts. When the time interval is 1 second, the participants perceive and are able to count 100% of the impacts. While the smaller interval tested (0.6s) shows a decrease of accuracy to 75%, we noticed a steep learning curve, meaning the users could perform fairly better even with very small intervals, provided that the device is capable to render them. Our prototype is physically limited to 0.6s.

Given the small sample size in our experiments, our results would require further testing in order to achieve statistical significance.

As future work, we would like to perform further testing in general. In particular, we would like to investigate the divergence in distribution for higher angles. Further testing and adaptation of the motion in the opposite direction would also be required, including a solution to move the mass at different speeds during the forward and return motion. Another interesting experiment would be to test the haptic feedback in conjunction with traditional virtual stimulus: sight and sound.

As an improvement to the hardware, we would like to explore other materials for the parts of the pendulum that are subject to intense stress, as one of them has ruptured during testing. We should also use better motors, such as brushless motors that are quieter and allow different speeds, together with encoders to feedback the actual angles. This would require also faster I/O and higher computation, which would all add to the cost of the device.

Altogether, the current prototype allowed us to prove the concept of a handheld force feedback device for VR with potential applications in games and 3D interaction.

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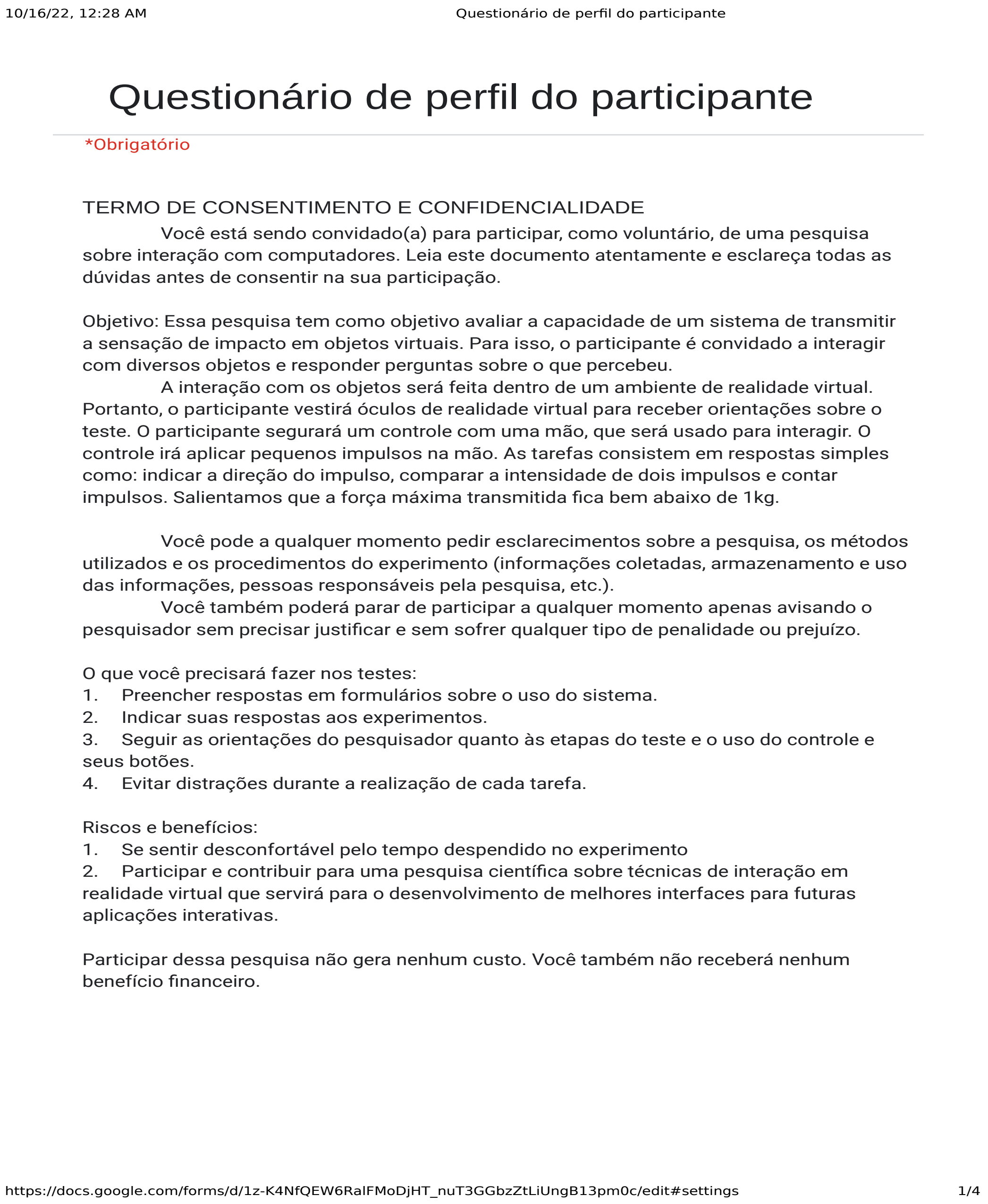
APPENDIX



Questionário de perfil do participante

*Obrigatório

TERMO DE CONSENTIMENTO E CONFIDENCIALIDADE

Você está sendo convidado(a) para participar, como voluntário, de uma pesquisa sobre interação com computadores. Leia este documento atentamente e esclareça todas as dúvidas antes de consentir na sua participação.

Objetivo: Essa pesquisa tem como objetivo avaliar a capacidade de um sistema de transmitir a sensação de impacto em objetos virtuais. Para isso, o participante é convidado a interagir com diversos objetos e responder perguntas sobre o que percebeu.

A interação com os objetos será feita dentro de um ambiente de realidade virtual. Portanto, o participante vestirá óculos de realidade virtual para receber orientações sobre o teste. O participante segurará um controle com uma mão, que será usado para interagir. O controle irá aplicar pequenos impulsos na mão. As tarefas consistem em respostas simples como: indicar a direção do impulso, comparar a intensidade de dois impulsos e contar impulsos. Salientamos que a força máxima transmitida fica bem abaixo de 1kg.

Você pode a qualquer momento pedir esclarecimentos sobre a pesquisa, os métodos utilizados e os procedimentos do experimento (informações coletadas, armazenamento e uso das informações, pessoas responsáveis pela pesquisa, etc.).

Você também poderá parar de participar a qualquer momento apenas avisando o pesquisador sem precisar justificar e sem sofrer qualquer tipo de penalidade ou prejuízo.

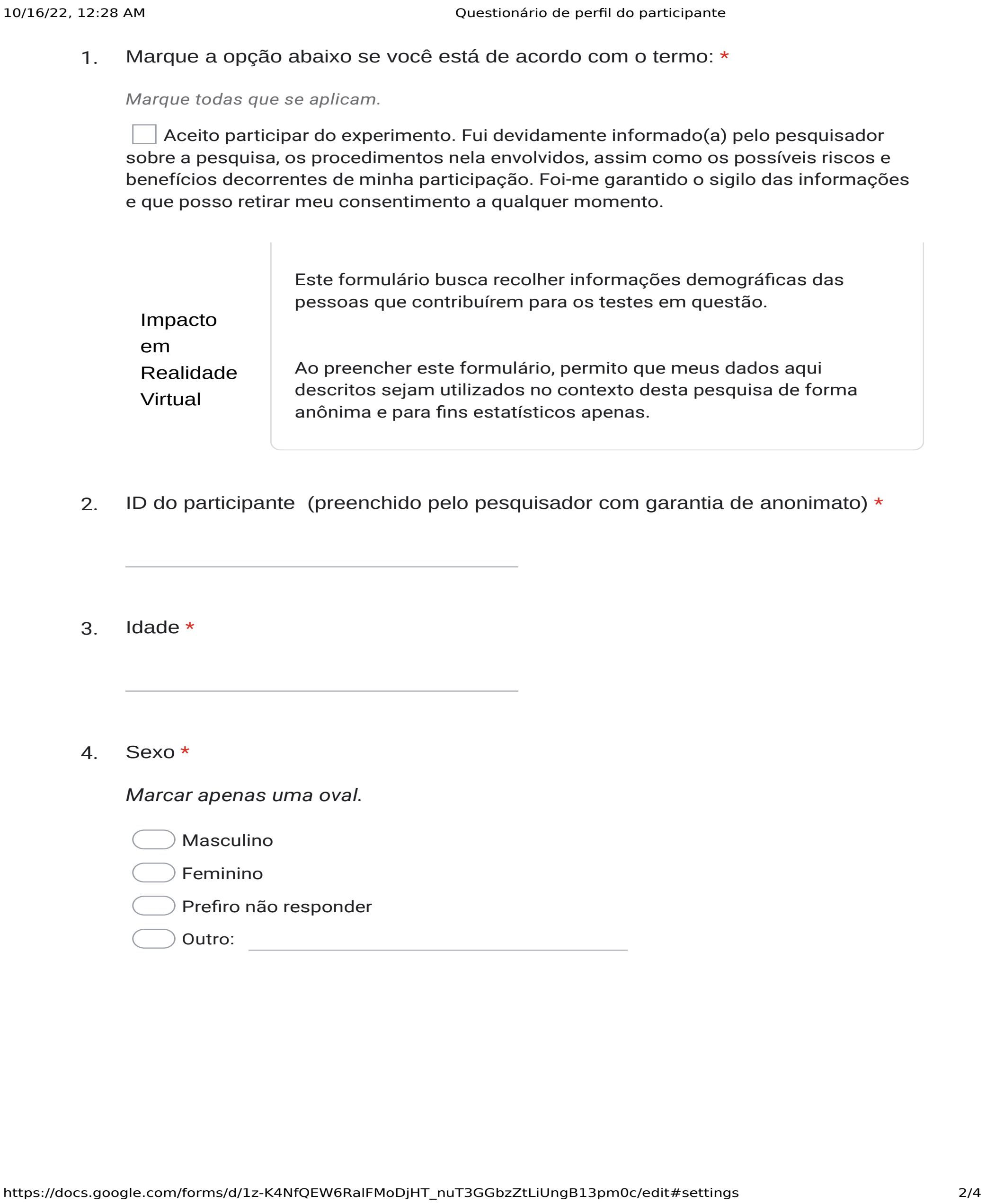
O que você precisará fazer nos testes:

1. Preencher respostas em formulários sobre o uso do sistema.
2. Indicar suas respostas aos experimentos.
3. Seguir as orientações do pesquisador quanto às etapas do teste e o uso do controle e seus botões.
4. Evitar distrações durante a realização de cada tarefa.

Riscos e benefícios:

1. Se sentir desconfortável pelo tempo despendido no experimento
2. Participar e contribuir para uma pesquisa científica sobre técnicas de interação em realidade virtual que servirá para o desenvolvimento de melhores interfaces para futuras aplicações interativas.

Participar dessa pesquisa não gera nenhum custo. Você também não receberá nenhum benefício financeiro.



10/16/22, 12:28 AM Questionário de perfil do participante

1. Marque a opção abaixo se você está de acordo com o termo: *

Marque todas que se aplicam.

☐ Aceito participar do experimento. Fui devidamente informado(a) pelo pesquisador sobre a pesquisa, os procedimentos nela envolvidos, assim como os possíveis riscos e benefícios decorrentes de minha participação. Foi-me garantido o sigilo das informações e que posso retirar meu consentimento a qualquer momento.

Impacto em Realidade Virtual

Este formulário busca recolher informações demográficas das pessoas que contribuírem para os testes em questão.

Ao preencher este formulário, permito que meus dados aqui descritos sejam utilizados no contexto desta pesquisa de forma anônima e para fins estatísticos apenas.

2. ID do participante (preenchido pelo pesquisador com garantia de anonimato) *

3. Idade *

4. Sexo *

Marcar apenas uma oval.

○ Masculino
○ Feminino
○ Prefiro não responder
○ Outro: ____________________

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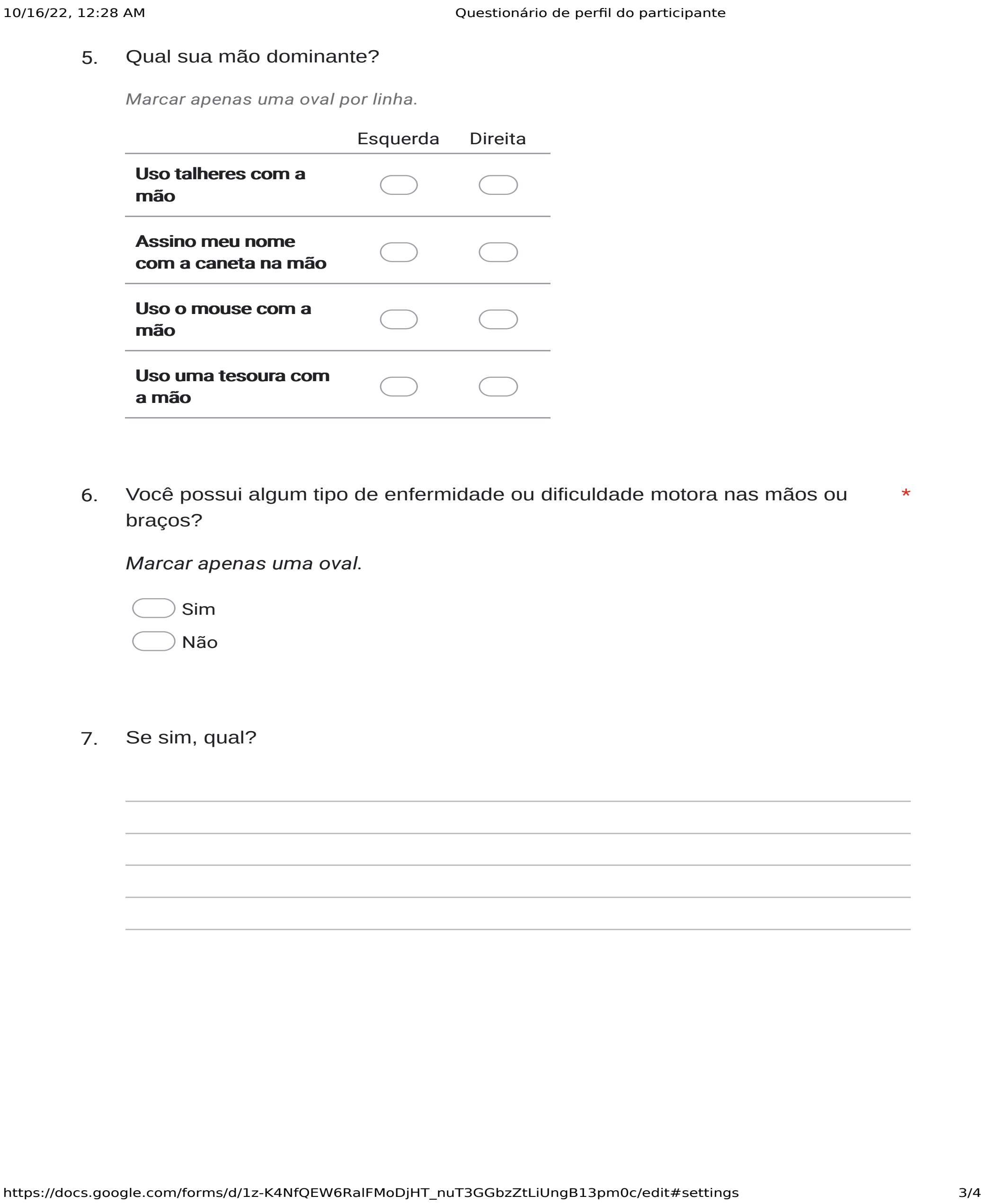


5. Qual sua mão dominante?

Marcar apenas uma oval por linha.

	Esquerda	Direita
Uso talheres com a mão	○	○
Assino meu nome com a caneta na mão	○	○
Uso o mouse com a mão	○	○
Uso uma tesoura com a mão	○	○

6. Você possui algum tipo de enfermidade ou dificuldade motora nas mãos ou braços? *

Marcar apenas uma oval.

○ Sim
○ Não

7. Se sim, qual?

8. Você possui alguma deficiência visual?

Caso tenha mais de uma, marque a primeira apenas

Marcar apenas uma oval.

- ○ Não
- ○ Miopia
- ○ Astigmatismo
- ○ Hipermetropia
- ○ Daltonismo/Discromatopsia
- ○ Outro: ____________________

Questionário - coleta de resultados

*Obrigatório

1. Id do participante *

____

2. Esse é a sua primeira rodada do experimento? *

Marcar apenas uma oval.

○ Sim
Pular para a seção 2 (Pré-experimento: Indique o quanto cada sintoma abaixo está afetando você neste momento:)

○ Não *Pular para a seção 4 (Prossiga para o experimento)*

Pré-experimento: Indique o quanto cada sintoma abaixo está afetando você neste momento:

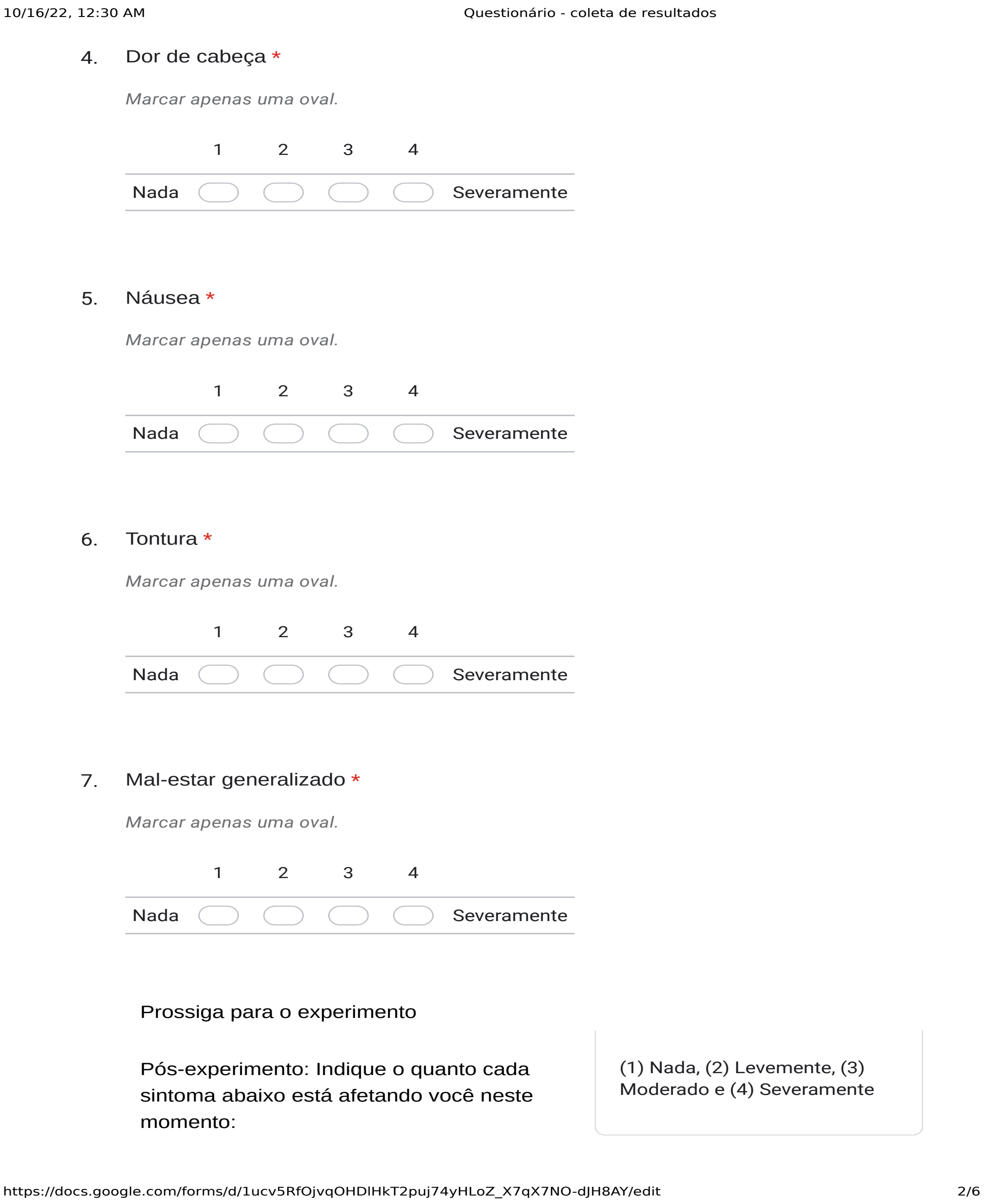
(1) Nada, (2) Levemente, (3) Moderado e (4) Severamente

Condições atuais

3. Dor muscular *

Marcar apenas uma oval.

	1	2	3	4	
Nada	○	○	○	○	Severamente



10/16/22, 12:30 AM Questionário - coleta de resultados

4. Dor de cabeça *

Marcar apenas uma oval.

	1	2	3	4	
Nada	○	○	○	○	Severamente

5. Náusea *

Marcar apenas uma oval.

	1	2	3	4	
Nada	○	○	○	○	Severamente

6. Tontura *

Marcar apenas uma oval.

	1	2	3	4	
Nada	○	○	○	○	Severamente

7. Mal-estar generalizado *

Marcar apenas uma oval.

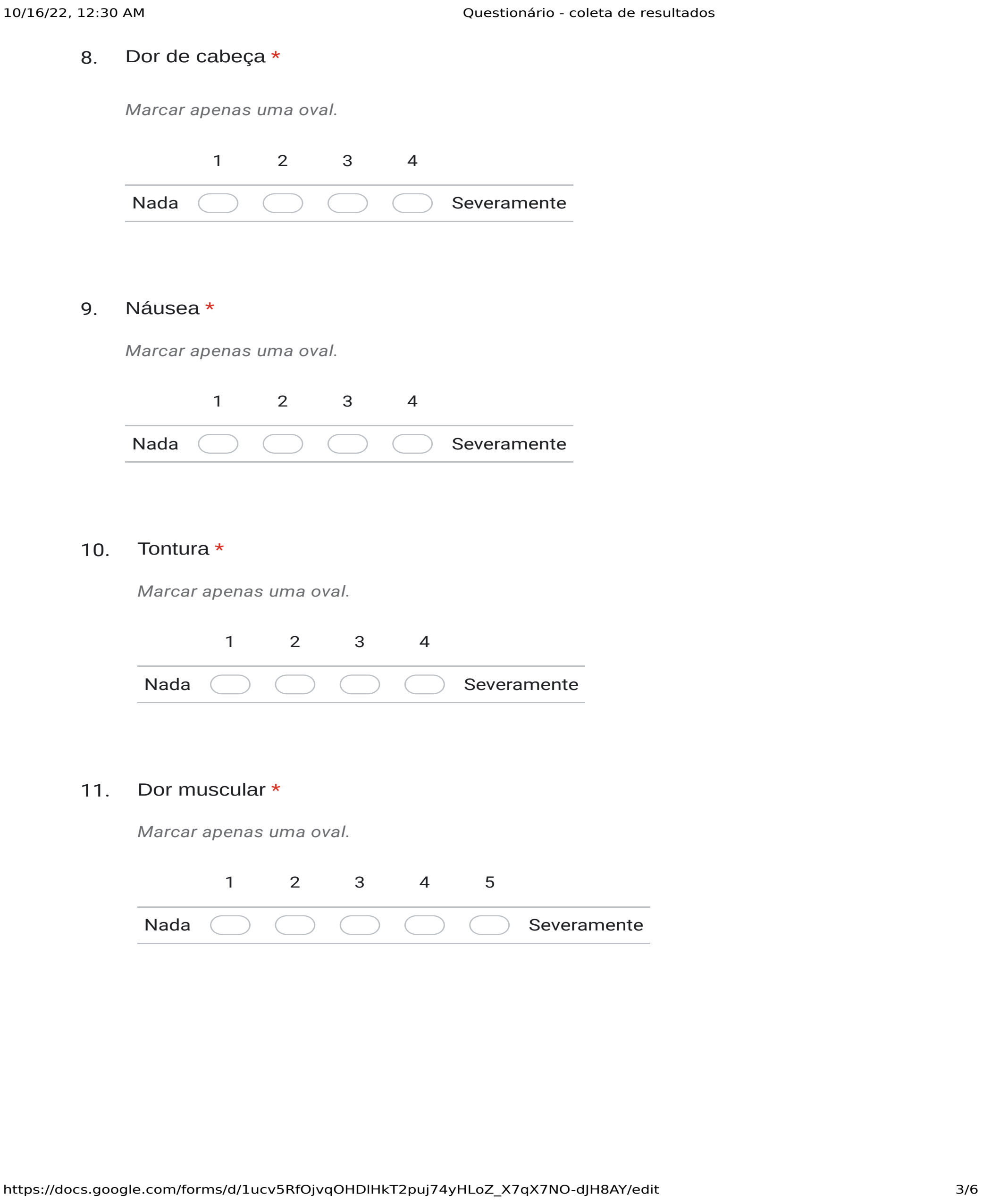
	1	2	3	4	
Nada	○	○	○	○	Severamente

Prossiga para o experimento

Pós-experimento: Indique o quanto cada sintoma abaixo está afetando você neste momento:

(1) Nada, (2) Levemente, (3) Moderado e (4) Severamente

https://docs.google.com/forms/d/1ucv5RfOjvqOHDlHkT2puj74yHLoZ_X7qX7NO-dJH8AY/edit 2/6



8. Dor de cabeça *

Marcar apenas uma oval.

	1	2	3	4	
Nada	○	○	○	○	Severamente

9. Náusea *

Marcar apenas uma oval.

	1	2	3	4	
Nada	○	○	○	○	Severamente

10. Tontura *

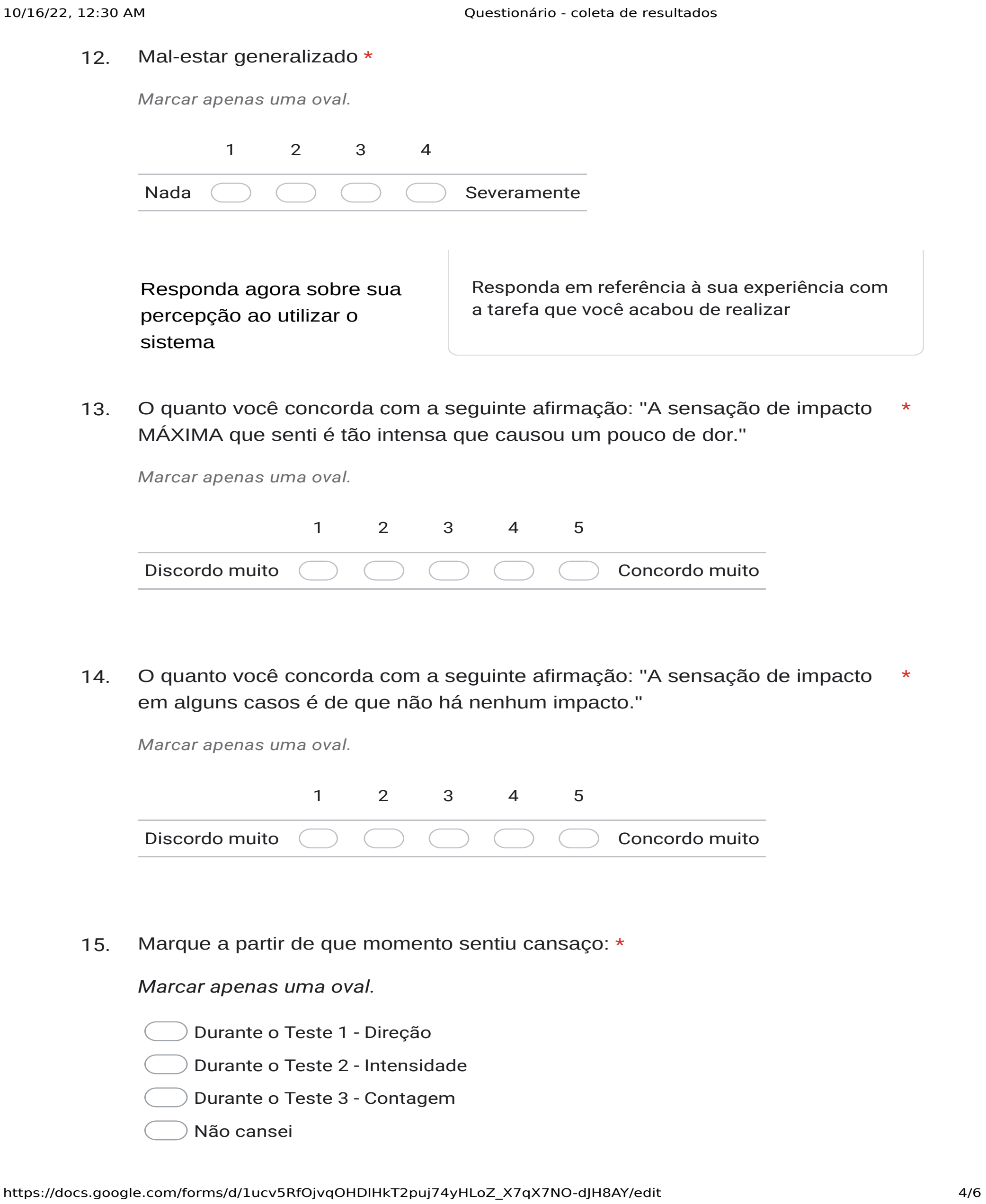
Marcar apenas uma oval.

	1	2	3	4	
Nada	○	○	○	○	Severamente

11. Dor muscular *

Marcar apenas uma oval.

	1	2	3	4	5	
Nada	○	○	○	○	○	Severamente



10/16/22, 12:30 AM Questionário - coleta de resultados

12. Mal-estar generalizado *

Marcar apenas uma oval.

	1	2	3	4	
Nada	○	○	○	○	Severamente

Responda agora sobre sua percepção ao utilizar o sistema

Responda em referência à sua experiência com a tarefa que você acabou de realizar

13. O quanto você concorda com a seguinte afirmação: "A sensação de impacto MÁXIMA que senti é tão intensa que causou um pouco de dor." *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo muito	○	○	○	○	○	Concordo muito

14. O quanto você concorda com a seguinte afirmação: "A sensação de impacto em alguns casos é de que não há nenhum impacto." *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo muito	○	○	○	○	○	Concordo muito

15. Marque a partir de que momento sentiu cansaço: *

Marcar apenas uma oval.

○ Durante o Teste 1 - Direção
○ Durante o Teste 2 - Intensidade
○ Durante o Teste 3 - Contagem
○ Não cansei

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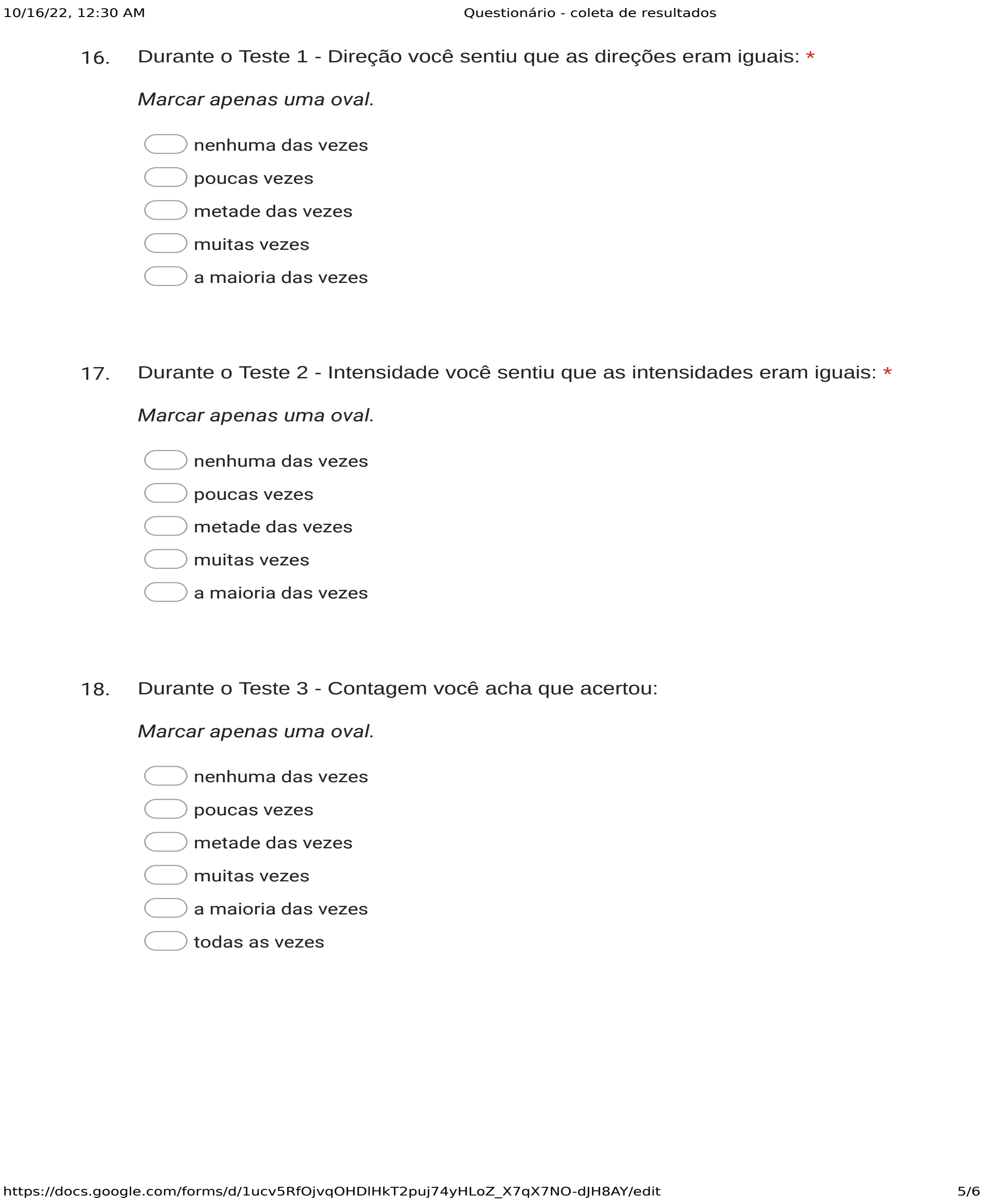

16. Durante o Teste 1 - Direção você sentiu que as direções eram iguais: *

Marcar apenas uma oval.

○ nenhuma das vezes
○ poucas vezes
○ metade das vezes
○ muitas vezes
○ a maioria das vezes

17. Durante o Teste 2 - Intensidade você sentiu que as intensidades eram iguais: *

Marcar apenas uma oval.

○ nenhuma das vezes
○ poucas vezes
○ metade das vezes
○ muitas vezes
○ a maioria das vezes

18. Durante o Teste 3 - Contagem você acha que acertou:

Marcar apenas uma oval.

○ nenhuma das vezes
○ poucas vezes
○ metade das vezes
○ muitas vezes
○ a maioria das vezes
○ todas as vezes

10/16/22, 12:30 AM Questionário - coleta de resultados

19. As tarefas são de percepção de força. Caso possa interpretar o estímulo percebido de outra forma, interpretaria como? Marque apenas a opção que considerar mais provável:

Marcar apenas uma oval.

- ○ nenhum - interpreto como peso mesmo
- ○ atrito
- ○ resistência
- ○ vibração
- ○ vento
- ○ peso
- ○ torque
- ○ inércia
- ○ movimento
- ○ cócegas
- ○ choque elétrico

Muito obrigado por suas respostas!

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