Medialogy Master Thesis
Interaction
Thesis: MTA171030
May 2017

Comparison of Movements in Virtual Reality Mirror Box Therapy for Treatment of Lower Limb Phantom Pain

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Summary

Context: Using Mirror Box Therapy (MBT) for treatment of Phantom Limb Pain (PLP) can reduce pain for some patients. The MBT has some limitations, such as: limited view through the mirror and the patient using it has to sit still to make the treatment work. Implementing the MBT to Virtual Reality (VR) can eliminate some of the limitations. Furthermore, using VR provides new possibilities to treat PLP.

Objectives: In this project, we investigate how anti-symmetrical mirroring compares to regular mirroring used in MBT for lower limb amputees, as several natural leg movements consist of moving anti-symmetrically, such as: walking, running and cycling. To further motivate the patients, a game is developed that uses cycling and swinging movements and incorporates them into goal-oriented tasks.

Methods: We implement the required movements into a game where the patient has to fly a gyrocopter through goal areas by using either symmetrical or anti-symmetrical movements. The experiments were implemented as a within-subject design, where the participants had to try the three versions of the game, and give preferential feedback.

Results: Two experiments were conducted. The preliminary experiment focused on the exertion rate of the three versions of the game. The findings showed that the cycling version was more exhausting than the swinging and symmetrical versions. Furthermore, we discovered that the required motions seemed too difficult and tiresome to do over a longer period of time. The final experiment focused on preferential data, and receiving feedback to the changes on the game implemented, after the findings from the preliminary experiment.

Conclusions: We found that anti-symmetrical movements are possible to use in VR MBT. However, the cycling motion was too strenuous for the participant to be able to perform over a longer period of time.

Keywords: Virtual Reality, Phantom Limb Pain, Mirror Box Therapy

Contents

1 Introduction

When people have a limb amputated due to accident or surgery a condition called Phantom Limb Pain (PLP) can occur. PLP is pain experienced the in the amputated limb and occurs for up to 85% of the amputees [11,24]. The PLP can relate to a certain movement or position of the phantom limb, as well as physical factors, such as: changes in weather or pressure on the residual limb [8]. PLP is not the same as having a physical pain and therefore the same treatments, such as local anesthesia and muscle relaxant, are not effective in treating it [8]. Different hypotheses to why PLP occurs have been explored, but the reason is still not known. One theory suggests that PLP is caused by the cortical area in the brain. Every part of the body is connected to a specific cortical area in the brain which creates a cortical map. But following an amputation, reorganization in the sensorimotor cortex may occur, due to deprived sensory input to the brain after amputation [13]. When amputated, the cortical region representing the amputated limb may be taken over by nearby cortical regions representing other parts of the body [13,21].

However, a method called the Mirror Box Therapy (MBT) has shown promising results in reducing PLP for some patients [22]. The MBT works by providing an illusion for the patient that they regain the missing limb. This is achieved by placing a mirror perpendicular to the patient. This way the intact limb is mirrored onto the phantom limb, as seen in Figure 1 (left). If positioned correctly, this creates the illusion that the amputated limb is still present. Why MBT is successful is unclear, but one hypothesis is that the cortical map is reorganized over time through limb stimulation [8,21]. The MBT is used both for lower limb and upper limb amputees. In the MBT for lower limb amputees, more requirements are needed in order to establish the illusion, as seen in Figure 1 (right). The patient needs to sit on a bed or a couch and must look into a mirror from a specific angle to establish the illusion. If the patient moves or looks away, the illusion will break. The patient further has limited movement, as the sitting position requires them to bend forward in order to into the mirror, while putting their weight onto the leg.

Figure 1: (Left): A picture placed perpendicular to the patient, which creates the illusion of a missing limb being present [29]. (Right): The setup required in order to perform the MBT for lower-limb amputees [14].

1.1 Related Work

1.1.1 Virtual Mirror Box Therapy

While the traditional MBT has produced promising results for treatment of PLP, there are potential advantages of developing a virtual MBT concept. In a virtual environment, there are less physical restrictions to maintain the illusion of the virtual limb in the mirror, as the patient would not need to sit in a fixed position. Furthermore, virtual MBT also enables the possibility to apply the MBT exercises into more meaningful tasks and in more motivating environments, such as games.

The concept of a virtual MBT have been explored in the past decade, together with the advancing technologies in motion sensors and the use of head-mounted displays (HMDs) for depth perception in virtual and/or augmented environments. Several virtual MBT concept proposals have been developed and a few systems have been tested with PLP patients. These concepts use an HMD or custom made display setups to visualize the system, and while most concepts use a Virtual Reality (VR) representation [6,16,20,23,28], a few have also developed augmented reality systems that implement a virtual limb to a representation of the stump of the patient [18,26]. To track the movements of the patients, several systems have been proposed, such as applying motion-detection gloves, motion sensors, or pre-rendered motions. The systems tested have shown promising results, as the patients have experienced increased control of the phantom limb by using some these systems [6,16,20], and others have experienced a short-term reduce in pain [20,23] as a result of the VR experiences.

Applying Meaningful Movements

In MBT, the exercise types used by the patients vary depending on the pain and disability state of the patient [30]. For upper-limb amputees the exercises include finger movements, hand rotations and arm movements. The patient usually start with a small basic movement. The movement is then repeated until the patient feels comfortable and ready to move onto a more challenging move. A similar approach is used for lower-limb amputees. Here, the exercises used focus on specific purposes, such as bending the knee, moving the foot, rotating the ankle and toe movements [5].

Even though the amount of lower-limb amputees are a lot higher than upper-limb amputees [5], most studies have focused on developing different meaningful movements to upper-limb amputees, such as: basic movement of the upper limb [16,18,20], punching an object [16], grabbing and releasing objects [6,23,28] and flexing the fingers [26]. But there have only been a limited set of meaningful movements explored for lower-limb amputees, such as kicking an object or tapping a drum pedal [6,16]. Furthermore, while the concepts proposed try to apply meaningful movements to the MBT exercises, most focus on applying standard mirrored movements. This makes sense as mirrored movements often occur when using both upper-limbs at the same time. The movements used with the phantom limb in the MBT, have a greater effect if they "feel" natural for the patient for them to be convinced they are moving their phantom limb [2]. This indication was found during a previous study, where three different mirrored applications were developed: (1) grabbing and releasing boxes, (2) pressing mirrored buttons and (3) a "bending game" in which the patient had to bend a virtual rod with both hands into different angles. While all three versions were able to apply meaningful movements, only the bending game was able to activate the feeling of using the phantom upper-limb when tested on an amputee [2]. Based on these results, we hypothesized that by applying mirrored movements, which required the use of both lower-legs would help lower-limb patients feel they used both their intact and phantom leg when playing the games [17]. Here, two different games were developed: (1) a shape game, where the user needed to move both feet into symmetrical square boxes in different angles, and (2) a slingshot game, where the user needed to grab the handle of a slingshot by doing a grabbing motion with their toes, aim the handle by moving their feet and release the handle by releasing their toes (see Figure 2). However, following an experiment with healthy subjects and a test with a lower-leg amputee, it was discovered that the mirroring movements were not enough, as the movements were either too abstract or too mundane [17]. It should be noted that this experiment also indicated the games were constraining to do as they required the participants to move their legs up in the air, in order to do the required movements.

Figure 2: (left): the shape game, develop in the previous semester, (right): the slingshot game.

Therefore, in order to develop a VR MBT concept that encourages the use of both lower-limbs, the concept developed must use motions that feel natural to do with both legs. Furthermore, the setup needs to be developed so it does not constrain the legs of the user, as these constraints would interfere with the overall experience and may stop the user from using both legs.

1.1.2 Body Ownership

In order to apply a virtual avatar as a convincing representation of the physical limbs in the virtual environment, it is important to consider which factors play a part in developing such a representation. Therefore, it is necessary to understand how to develop body ownership with a virtual avatar, for the user to feel the body belongs to them and they are the ones performing the actions. Body ownership can be defined as sensing which body parts belong as a part of our body and which does not. Establishment of body ownership is done through the input of multiple sensors working together to define what belongs to our body and what does not. Body ownership can be seen as a combination of the sense of agency; "*that I am the one who is causing or generating the action*" and the sense of ownership; "*that I am the one undergoing this experience*" [9]. Body ownership is established through multiple sensory inputs working together, like: vision, tactile feedback, kinesthetic sense and the proprioceptive sense, i.e. the sense of one's own bodily position. It is possible to achieve the feeling of body ownership without input from all senses as long as the inputs are not contradicting [1,4]. It is also possible to establish body ownership with external limbs, such as a physical artificial or a virtual limb [25]. When establishing body ownership with artificial body parts it is necessary to consider the factors that plays into the establishment. These factors can be put into three focus areas: (1) sensory synchronicity [4,7], (2) positioning of the external limbs [4,10] and (3) sensory acceptance [2,12,27].

Sensory Synchronicity

In order to establish body ownership with an artificial body part, the sensory input must be synchronous. If the inputs are synchronous, it is possible to achieve body ownership with an artificial body part, within 10-30 seconds [7]. However, contradicting input will break the illusion [4]. When developing a virtual avatar it is therefore necessary to make sure the visual movements of the virtual avatar corresponds to how the user feels the real limbs are moving, based on their proprioceptive- and kinesthetic senses. Furthermore, if the frames per second of the virtual representation is too low, this will develop lagging movements of the virtual avatar, which may contradict with the sensory input.

Limb Positioning

While the positioning of the artificial limbs are important based on the positioning of the real limbs, it is possible to establish ownership with an external limb that is positioned up to 24 cm away from the real limb [4,10]. When the establishment of ownership for the artificial limb has occurred, it is possible to maintain the illusion even if the positioning between the real and artificial limb changes, as long as this shift of placement is not an abrupt shift [10]. The human body will adjust to the mental limb positioning of the active limb, in what is called the "proprioceptive drift" [4]. Therefore, as long as the body ownership has been established, it is possible for the virtual limbs to drift into incorrect positions at times, as long the drift is not into too extreme.

Sensory Acceptance

As mentioned earlier, it is not possible to establish ownership with an artificial limb, if different sensory input contradict with each other. For example, having both the real and artificial limb within visual range will make it impossible to establish body ownership, as it is only possible to establish ownership with one of the limbs at a time [12]. Furthermore, the external limb must be within an acceptable visual shape in order to establish ownership. For example, a wooden squared hand is too abstract to develop ownership, but a rubber hand is not [27]. Furthermore, it is possible to establish ownership with a robotic hand as long as it behaves as a human hand [2]. However, if the artificial or virtual body part appears almost like a real body part, but not completely, the user can develop an eerie feeling and dislike the body part [15]. Therefore, if a complete replica of the real body part should be used, it should be done through filmed or augmented implementations. The size of the virtual limbs are also important to consider as a correctly sized virtual body, compared to the given user, will create better results, though it does not need to be the exact size [25]. Therefore, creating a completely identical virtual body would not be necessary. The virtual avatar in this project should represent the participant well enough in size and proportions and should look somewhat close to their real body.

1.2 Summary

While the long term goal is to design a VR version of MBT to alleviate PLP, the goal for this project is to encourage movement of both legs, and engage users by having them play a game while using both legs. The focus of this project is on lower-limb amputees and anti-symmetrical movements. The anti-symmetrical movements are implemented and compared with standard symmetrical movements. The user will be sitting down and having the feet above the ground to not constrain the legs. The avatar used should be able to visually represent the movements the user is making, such as: bending the knee, moving the foot, and rotating the ankle. Furthermore, the movements of the avatar should be synchronous with the user's movements to achieve body ownership to the avatar.

2 Design & Implementation

It was decided to develop a system using VR technology that applied mirroring methods other than standard mirroring for lower-limb MBT. Therefore, three movement versions for the game were developed; two anti-symmetrical movements and a regular mirrored version for comparison:

- (1): Anti-symmetrical version: This version is based on a simple anti-symmetrical movement, such as walking, as the user needs to move the controlled leg in a back and forward swinging motion, as seen in Figure 3, (1). The mirrored limb then follows this motion in an anti-symmetrical manner.
- (2): Cycling version: This version is based on applying cycling motions. Here, the user needs to perform circular motions with the controlled leg, as seen in Figure 3, (2). The mirrored leg then performs inverted movements, so the leg will do anti-symmetrical movements both in the up/down and forward/backwards directions.
- (3) Symmetrical version: In this version the user needs to move the controlled leg in a back and forward motion, similar to the anti-symmetrical version. However, here the mirrored leg follows this motion. The purpose of this version is to use as a control version for comparison.

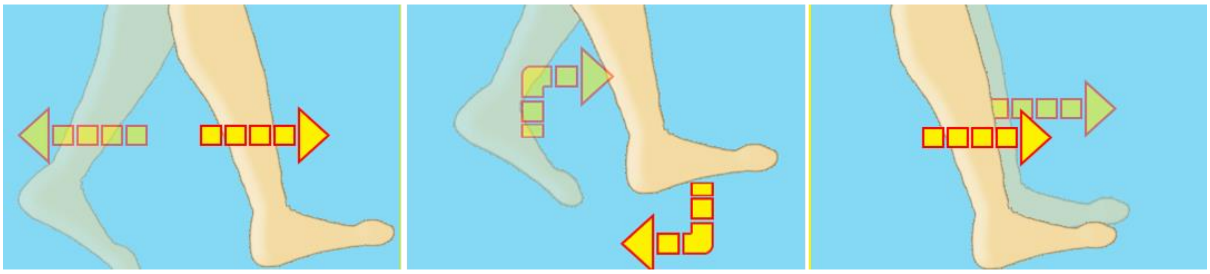

Figure 3: The three movement versions used in the game: (1) The anti-symmetrical version, (2) The cycling version, and (3) the symmetrical version.

The user applies one of the three movements to control the altitude level of a gyrocopter. The game consist of yellow transparent checkpoints that the user has to fly into, to collect points.

2.1 The Virtual Avatar

The avatar used was found through the Unity asset store. The two avatar models used in this project are free-to-use “Lite” versions of avatars developed by the Morph3D team [31]. The avatars fit nicely to this project as both the male and female are built for the Unity Animator system with the models in an accepted T-pose and with bones correctly attached. When playing the game, the user is able to control one leg of the avatar through the HTC Vive controllers. The other leg moves based on the input of the controlled leg by either mirroring the movements (standard), mirroring anti-symmetrically backwards and forwards (anti-symmetrical), or mirroring anti-symmetrically backwards and forwards, and upwards and downwards (Cycling). Since the focus should be on the legs, the arms were moved back so the user would not see them. The head of the avatar was moved away from sight, because it would interfere with the cameras from the HMD. A picture of the avatar can be seen in Figure 4.

Figure 4: The male avatar used for the game.

2.1.1 Calibration Phase

Before being able to control the avatar, a calibration phase is initiated. The user is instructed to sit in a specific position with the legs at the same height and the feet pointing directly forwards towards where the user is looking. The HTC Vive controllers are attached to the thigh and foot of the user. The position of the controlled foot and knee is calibrated using the position and orientation of where the user is sitting. A picture of the seating position in the calibration phase can be seen in Figure 5. When calibrating, the position of the avatar moves to where the HMD is located in the VR environment. The avatar switches to a seating position and the controlled leg of the avatar is positioned where the user's controllers are situated in the VR environment. The scaling of the avatar can be adjusted to fit the size of the user. This is done to have the controls and mirroring of the avatar as precise as possible.

Figure 5: Calibration phase position.

2.2 Animating the Avatar

2.2.1 Upper Body Movement with HMD

When the user is moving the upper body in the VR environment, the avatar follows along. This is achieved by rotating the spine of the avatar in relation to the position of the HMD. This is an important feature because the user sees the upper body of the avatar, and therefore the movements of the avatar must move realistically with the user. See Figure 6.

```
if (null != headBone && calibrationProcess == true)
{
    Vector3 lookDir = headMarker.position - chestBone.position;
    Vector3 forward1 = Vector3.Cross (lookDir, helicopter.transform.right);

    //Apply parent rotation (inverse) * new look rotation, using the forward and look directions
    animator.SetBoneLocalRotation (HumanBodyBones.Spine, Quaternion.Inverse (spine.parent.rotation)
    * Quaternion.LookRotation (forward1, lookDir));
}
```

Figure 6: Moving the upper body of the avatar.

2.2.2 Movement of Controlled Leg

The controlled leg is animated based on the position and orientations of the HTC Vive controllers attached to the leg of the user. An offset position of the controller which is attached to the foot is applied as a target of the controlled foot. See Figure 7. The *lfMarkerAnchor* applies an offset so the position of the controller fits the ankle joint of the avatar. The animator IK (Inverse Kinematics) component then adjusts the leg so it moves accurately based on the current foot position. The other controller attached to the thigh is used to set the orientation of the upper leg. This is done by applying the position of the controller by using the *SetIKHintPosition*. See Figure 7, line 276-277. This function is used to hint a position of the knee of the avatar.

```
animator.SetIKPosition (AvatarIKGoal.LeftFoot,
    swapControllers.activeFoot.TransformPoint (lfMarkerAnchor));
animator.SetIKRotation (AvatarIKGoal.LeftFoot, swapControllers.activeFoot.rotation);
```

```
275 animator.SetIKHintPositionWeight (AvatarIKHint.RightKnee, 1.0f);
276 animator.SetIKHintPosition (AvatarIKHint.RightKnee,
277     swapControllers.activeLeg.TransformPoint (new Vector3 (0.0f, 0.05f, 0.0f)));
```

Figure 7: (Top script): Moving the foot, based on the controller position. (Bottom): Moving the knee.

2.2.3 Movement of Non-controlled Leg

Mirroring

We used the same method as we did on 9th semester, except this time we had the avatar at position *(0,0,0,)* which made it easier to calibrate the mirror position. The mirroring of the position is done by using the inverse position of the controlled foot in the X-axis (left and right for the user), and using the same Y and Z position. The mirroring of the rotation is done by using the Unity vector3.Reflect function which takes a vector and reflects this position off a plane, i.e. a plane's normal that is perpendicular to its surface [32]. The Vector3.Reflect takes two arguments: A mirror plane and the vector to reflect. In this project the mirror plane is defined in the calibration phase by orientation of the HMD, and the vector to reflect is the orientation of the controller attached to the foot. This can be seen in Figure 8, line 311-314. To get the inverted position, the controller position is subtracted to the mirror plane. The rotation is mirrored by applying the Unity *SetLookRotation*, which uses the Quaternion.SetLookRotation to create a rotation with specified forward and upwards directions [33].

```
302 //Standard Mirror Position to other foot
303 if (swapLegControls.legMirrorVersions == 0)
304 {
305     Vector3 mirroredPos = new Vector3 (-swapControllers.activeFoot.TransformPoint (lfMarkerAnchor).x,
306     swapControllers.activeFoot.TransformPoint (lfMarkerAnchor).y,
307     swapControllers.activeFoot.TransformPoint (lfMarkerAnchor).z);
308     animator.SetIKPosition (AvatarIKGoal.RightFoot, mirroredPos);
309
310     //Mirror Rotation to other foot
311     reflectedRotation.SetLookRotation (Vector3.Reflect (swapControllers.activeFoot.transform.forward,
312     calibMirrorPlane.mirrorNormal), Vector3.Reflect (swapControllers.activeFoot.transform.up,
313     calibMirrorPlane.mirrorNormal));
314     animator.SetIKRotation (AvatarIKGoal.RightFoot, reflectedRotation);
315 }
```

Figure 8: Script of the standard mirroring.

Anti-Symmetrical

In the anti-symmetrical mirroring version, the same principle of standard mirroring applies with an added extension. The anti-symmetrical version uses a point that is positioned between the legs of the avatar. A new Z-value that is applied to the Z-axis, is calculated from this point which makes the mirrored leg move in the opposite forward and backward direction. The rotations were inversed in the X-axis, but with some minor adjustments to make the mirrored rotation look more natural when the feet were far apart from each other. The anti-symmetrical function can be seen on Figure 9.

```
//Swinging Mirror Position to other foot
if (swapLegControls.legMirrorVersions == 1)
{
    float newZvalue = swingPos.position.z - zDistOffset;
    Vector3 mirroredPos = new Vector3 (-swapControllers.activeFoot.TransformPoint (lfMarkerAnchor).x,
    swapControllers.activeFoot.TransformPoint (lfMarkerAnchor).y, newZvalue);
    animator.SetIKPosition (AvatarIKGoal.RightFoot, mirroredPos);

    //Mirror Rotation to other foot
    reflectedRotation.SetLookRotation (Vector3.Reflect (swapControllers.activeFoot.transform.forward,
    calibMirrorPlane.mirrorNormal), Vector3.Reflect (swapControllers.activeFoot.transform.up,
    calibMirrorPlane.mirrorNormal));
    Vector3 newRot = reflectedRotation.eulerAngles;

    animator.SetIKRotation (AvatarIKGoal.RightFoot, Quaternion.Euler (-newRot.x + 25.0f, 180.0f, 0.0f));
}
```

Figure 9: Applying anti-symmetrical movements.

Cycling

The cycling movement is done in the same manner as anti-symmetrical, along with a new Y value to make the legs move up and down anti-symmetrically. The function can be seen in Figure 10.

```
//Cycling Version: Mirror Foot Position to other foot
if (swapLegControls.legMirrorVersions == 2)
{
    float newZvalue = swingPos.position.z - zDistOffsetCycling;
    float newYvalue = swingPos.position.y - yDistOffset;

    Vector3 mirroredPos = new Vector3 (-swapControllers.activeFoot.TransformPoint (lfMarkerAnchor).x,
    newYvalue, newZvalue);
    animator.SetIKPosition (AvatarIKGoal.RightFoot, mirroredPos);

    //Mirror Rotation to other foot
    reflectedRotation.SetLookRotation (Vector3.Reflect (swapControllers.activeFoot.transform.forward,
    calibMirrorPlane.mirrorNormal), Vector3.Reflect (swapControllers.activeFoot.transform.up,
    calibMirrorPlane.mirrorNormal));
    Vector3 newRot = reflectedRotation.eulerAngles;
    animator.SetIKRotation (AvatarIKGoal.RightFoot, Quaternion.Euler (-newRot.x, newRot.y, newRot.z));
}
```

Figure 10: The cycling movement.

2.3 The Gyrocopter

In order to apply the three different leg movements into more purposeful applications, it was decided to let the user control a gyrocopter through these movements. The features of a gyrocopter is similar to a standard helicopter, just designed in a much smaller scale and typically only have room for the pilot. Gyrocopters often have no, or only a few, windows. Therefore the pilot has an almost clear view around their position. A gyrocopter has rotator blades on top of the chassis to apply the upwards force and a set behind to apply forward motion. The main difference between standard helicopters and gyrocopters is the velocity and altitude capabilities, as gyrocopters are not capable of achieving the same velocities or altitudes as standard helicopters. A gyrocopter model was developed to imitate a real gyrocopter to some degree, with features such as a wing-tail and rotor-blades. Features from a real cockpit panel were implemented. Other features needed to be designed so they would fit the requirements for applying the different leg movements. The gyrocopter developed for this project can be seen in Figure 11.

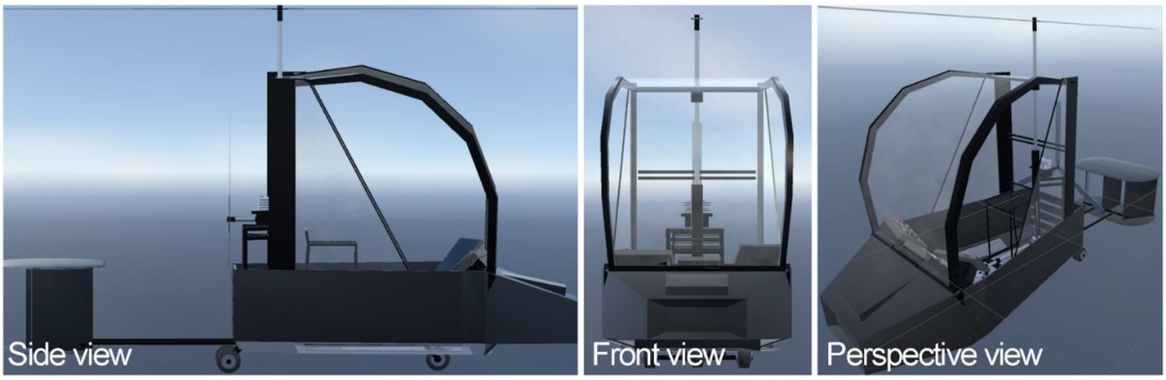

Figure 11: The gyrocopter used in the games. (Left): side view, (middle): front view, (right): perspective view.

Within the virtual gyrocopter the user is positioned onto a high-chair within the gyrocopter cabin. The user is positioned so the virtual legs are hanging down from the chair, but without touching the ground. The user controls the upward and downward movement of the gyrocopter through one of the three leg movements, depending on which version is activated by the facilitator, and a forward motion is applied automatically in a steady motion, after the user decides to take off. In order to avoid an unsettling feeling of hanging in the air, it was decided to implement a full chassis to the gyrocopter, but with windows to keep the visual range as high as possible. A big front window was implemented and small windows were applied to the sides. Furthermore, the floor of the chassis was included with small windows to help navigating the helicopter when going downwards and to encourage the user to look down towards the legs.

2.3.1 Movement and Orientation Restrictions

In order to avoid discomfort when playing the game, it was important to design the gyrocopter so the virtual world orientation did not change, compared to the real orientation of the user. Therefore, the orientation of the gyrocopter was locked into the same orientation and only movements in the Y (up/down) and Z (forward) axes could be applied.

2.3.2 Adding Force to the Gyrocopter

Motion was applied to the gyrocopter using the Unity physics engine. The gyrocopter was applied with a Rigidbody, a mass of 100 kg, and had force applied in the upwards and forward motion, depending on the status of the game. Gravity was applied to the gyrocopter, which meant a constant force of 9.81m/s2 in the Y-axis was applied at all times. To compensate the gravity a constant upward force of 800 was applied to the gyrocopter to simulate a slow downward pace. Whenever the user applied force, a base amount was applied to the gyrocopter in the Y-axis. However, if the gyrocopter was moving down at certain velocity, more force would needed to compensate. Therefore, a function was implemented to check the current velocity status of the gyrocopter in the Y-axis at the time the user would apply force. The function then compensated for the current velocity by either adding more force to the thrust applied by the user, or by reducing the amount, if the gyrocopter reached a certain positive velocity. Furthermore, the function would also check if the gyrocopter reached a certain downward velocity and then add more force. This was done to prevent the gyrocopter from falling down at a pace too high to be comfortable to experience. Forward motion was applied automatically when the user started the game by lifting the gyrocopter above the ground. The forward force applied made the gyrocopter accelerate to a certain velocity. When this velocity was reached, the gyrocopter would stop applying force and stay in the same velocity.

2.3.3 User Input

The user was able to decide when to apply the upward force through their leg movements. This was done by tracking the change in position in the Z-direction of the given HTC Vive controller attached to the foot, as seen in Figure 12, and comparing the new position with the position in the previous frame. The current position of the gyrocopter was taken into account for each frame, as seen in line 39. Whenever the user moved the leg, and thereby also the controller above a preset velocity, force was applied to the gyrocopter. This forced the user to move the feet at a certain pace in order to move the gyrocopter. This approach was used for both the symmetrical and the anti-symmetrical versions of the game. However, in the cycling version the change in Y-position was also included. This was done to make sure the user would be able to apply force when doing circular motions.

```
38        //Force Manager HTC VIVE Controller --------------------------------------//
39        zDirection = swapControllers.activeFoot.position.z - gyroCopter.transform.position.z;
40        velocity = (zDirection - lastZ) / Time.deltaTime;
41        lastZ = zDirection;
```

Figure 12: How the system checked for the current change of position of the controlled HTC Vive controller in the z-direction.

2.3.4 The Panel

In order to help the user navigate the gyrocopter, a panel was designed which visualized different type of information about the flight and game status. The panel was positioned in a low position compared to the position of the user as this allowed the user to look at the features on the panel while still being able to have the virtual legs within their line of sight. The panel setup can be seen in Figure 13.

Figure 13: The position of the gyrocopter panel and virtual avatar of the user.

The panel included features designed for different purposes. An overview of the panel can be seen in Figure 14. The features of the panel includes:

- *Navigational tools*: A GPS screen (Figure 14, number. 1) was implemented which displayed a real-time top-down view of the gyrocopter. Its main purpose was to visually view the distance from the gyrocopter to the nearest checkpoint, which was indicated on the screen as a yellow circle. An altitude meter was implemented (Figure 14, number 3), which displayed the current height of the gyrocopter through a red arrow and the altitude of the nearest checkpoint, displayed through a green arrow.
- *Point system*: A small screen displaying amount of points gathered was positioned in the middle of the panel for the user to easily view their current score.
- *Speedometer*: A speedometer was positioned to the far right (see Figure 14, number 4) of the panel. The speedometer helped the user viewing the current speed of the gyrocopter and to help explain when the gyrocopter was accelerating. Similar to the altitude meter, the current speed was visualized through a red arrow.

Figure 14: An overview of the panel in the gyrocopter. (1): the GPS screen, (2): the point system, (3): the altitude meter, and (4): the speedometer.

2.4 The Levels

Two levels were developed for the gyrocopter game. Both levels take place in an open world with water and small islands. The open world was chosen to avoid a claustrophobic environment. The two levels are approximately the same length, but the designs are different as level one was designed for the preliminary experiment and level two for the final experiment.

2.4.1 Checkpoints

To encourage the user to apply leg movements through the level at certain velocities, checkpoints were added throughout the level, as seen in Figure 15. The checkpoints are semi-transparent and rotate clockwise at a slow, steady pace. They are provided with a box collider and a *OnCollisionEnter()* script that checks if the gyrocopter collides with the checkpoint. If so, the user is awarded with a point and a "bling" sound is played and the checkpoint disappears. However, if the user misses the checkpoint, either by flying beneath or above it and thus not hitting the collider, no points are awarded and a negative "buzz" sound is played.

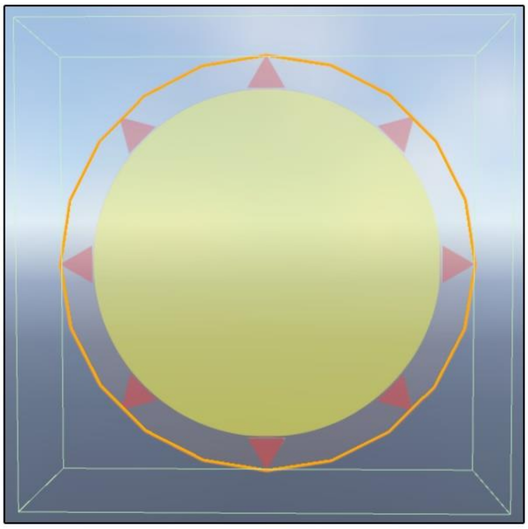

Figure 15: The checkpoints used in the game.

2.4.2 Bouncing Colliders

Altitude restrictions were applied to the game, to make sure the gyrocopter did not fly too high in the air or below the water surface. Whenever the gyrocopter would drop to 5 meters above the water surface, a force would be applied which gently bounced the gyrocopter up with about 10 meters. Similarly, if the gyrocopter would increase its altitude to 250 meters, no force would be able to be applied until the gyrocopter would drop in height. As the levels also had islands included with different altitudes, bouncing colliders were applied manually above the surface, as seen in Figure 16. These colliders were applied with an *OnCollisionStay()* function and would continuously apply a small force to the gyrocopter until it bounced upwards and exited the collider again.

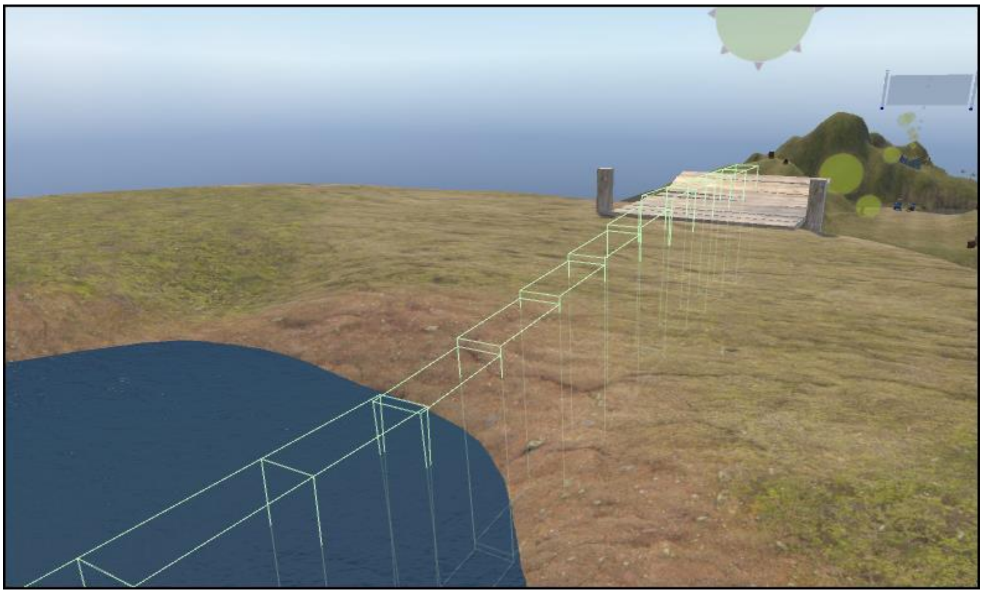

Figure 16: The bouncing colliders applied throughout the levels.

2.4.3 FPS Restrictions

In order to withhold the frame rate at an acceptable level, some restrictions were necessary to apply. Many objects in the level were removed or simplified to lower the amount of objects needed to be rendered. Furthermore, a plane with a simplified water shader was applied. Lastly, the clipping plane of the head-mounted display was reduced to 2000. This means that the user would not be able to look all the way to the finish-line, from start. But this range was still wide enough to make it hard to notice the edges of the ocean, and to have the islands visible at all times.

3 Preliminary Test

This section describes a preliminary experiment which evaluated the exertion rate of the three different types of movements, used in the game.

3.1 Design and Participants

Based on our previous semester project [17], it was hypothesized that some leg movements may cause a high exertion level, which limits the usability of these movements as the exercises in the game should be playable for several minutes. Besides the exertion rate, the performance of the three different leg movements were evaluated. Finally, the participants were to rank which version they preferred to check if they favored one of the anti-symmetrical versions, compared to the symmetrical mirrored version. Therefore, we looked into the following focus areas:

- To evaluate the exertion rate of the participant, following the completion of each version in the fatigue level
- The performance of the movements required in each of the three game versions
- Which version of the game was preferred

9 healthy participants were recruited at Aalborg University to participate in the experiment. The experiment was conducted in a within-subject design as all participants were instructed to play through all three versions of the game. The order of play was randomized in a counterbalanced order, to remove carry-over effects.

3.2 Setup

The experiment was conducted in a controlled environment in a lab at Aalborg University. The participants were instructed to sit on a high metal chair at a specific location in the lab as seen in Figure 5 in chapter 3. The experiment was conducted using an HTC Vive head mounted display and two controllers attached to the controlled leg. The controllers were attached through a custom made Velcro and rubber band setup as seen in Figure 17. Following each movement version, the participants were instructed to rate the exertion level, based on a Borg rating scale. This rating was conducted following the completion of a single version, as their exertion rate would still be fresh in their memory and the participants would get a small rest period before the next iteration. The leg performance was evaluated through ranked answers using Likert-Scale item questionnaires.

Figure 17: The setup of the controllers.

3.2.1 Borg Scale

The Borg Scale is a way of measuring physical activity intensity level. Perceived exertion is how hard you feel like your body is working. It is based on the physical sensations a person experiences during physical activity, including increased heart rate, increased respiration or breathing rate, increased sweating, and muscle fatigue. Although this is a subjective measure, a person's exertion rating may provide a fairly good estimate of the actual heart rate during physical activity [3].

3.3 Procedure and Participants

The participants received a brief introduction to the test and had the controllers applied to the left leg. The participants were then introduced to the three different movement versions, as a facilitator sat on the chair and visually showed the movements needed. Following the introduction, the participants were instructed to complete a level while hitting as many of the checkpoints as possible. The level takes about 3.20 minutes to complete. The checkpoints in this level are positioned in waves, i.e. long up- and down going movements, which encourages the participants to apply continuous legs movements for longer periods of time.

This was designed with the purpose of having the participants applying the leg movements for a steady amount of time. Following the completion of a level, the participant was asked to complete a questionnaire in which they rated the exertion level and performance of the leg movements of the given version. Following the completion of all three versions a post-test questionnaire was answered.

3.4 Results

9 students in the age of 21-27 from Aalborg University participated in the experiment. All participants had previous experience with virtual reality and 4 participants were using virtual reality regularly.

3.4.1 Exertion Rate

The exertion rate of the participants were evaluated through the Borg scale rating [3]. The Borg scale rating ranges from 6 to 20, with 6 being equal to "no fatigue at all", 9 being "very light exercise - like walking slowly", 13 being "somewhat hard, but still manageable", 17 being "very strenuous - the person needs to push himself and gets very tired, and 20 - "extremely strenuous". The numbers range from 6 to 20, because they somewhat correlate with the heart rate of the participant, if multiplied by 10.

The participants did not feel the standard symmetrical version was exhausting to play as it received a mean value of 9.53, which is similar to "very light exercise" and only one participant rating it above 11, as seen in the box plot in Figure 18. The anti-symmetrical version also received a low exertion rating as the mean answer was 9.33 and also only one participant rating this version above 11. The cycling version, however, received a mean answer of 13.89 which corresponds to "somewhat hard".

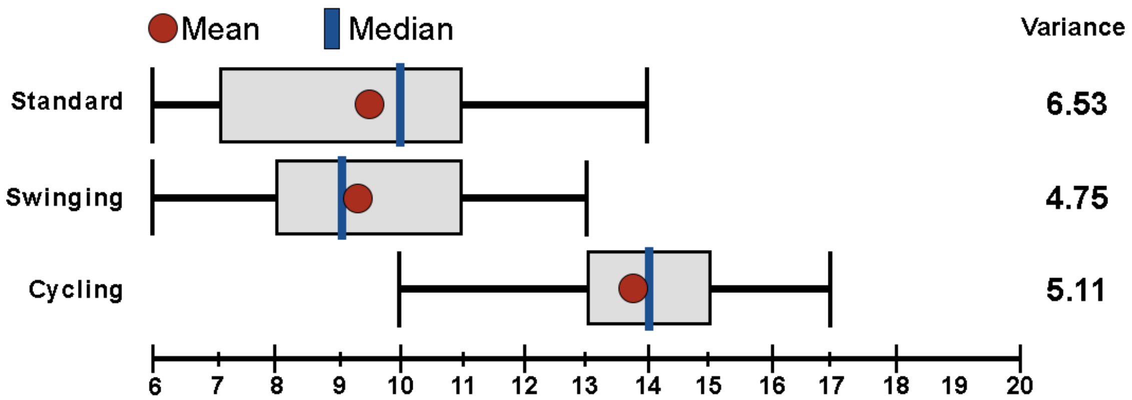

Figure 18: The exertion rate results.

Following each version the participants were asked to specify which kind of discomforts they experienced, if any. The symmetrical movement version received 3 "yes" and 6 "no". The discomforts were: (1) strained muscles, (2) blurred vision and (3) sweating under the HMD. The anti-symmetrical version received 1 "yes": (1) sweating under the HMD and 8 "no". The symmetrical received 5 "yes" and 4 "no". The discomforts included: (1) strained muscles, (2) sweating under the HMD and (3) Other: "mild pain in hip-area".

3.4.2 Leg Movements

The leg movements were evaluated through two Likert-scale questions, ranging from 1: strongly disagree to 7: strongly agree. The two questions were (1): "I found the leg movements easy to perform", and (2): "The leg movements felt natural to perform".

Both the standard symmetrical movements and the anti-symmetrical received positive results, as both received a median value of 7: strongly agree, both a mean value of 6.44 and with a low answer variance, as seen in Figure 19. The cycling version received mixed results as the answers had a variance of 2.50 with a mean value of 4.67.

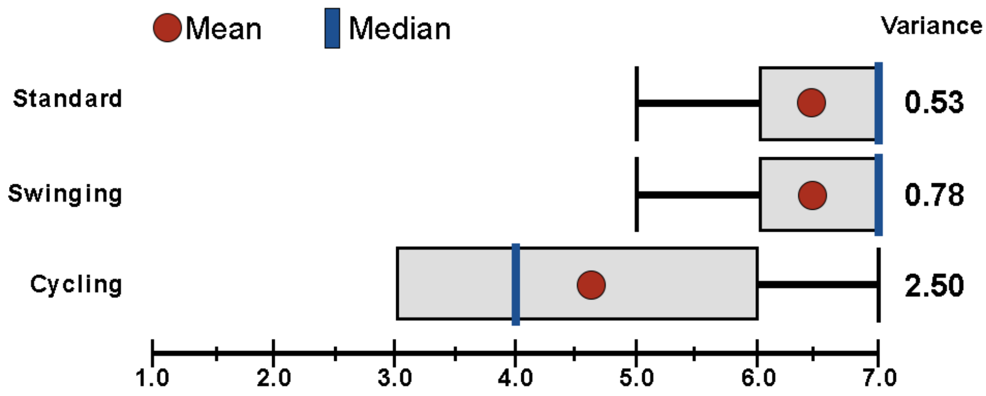

Figure 19: Answers to (1): “I found the leg movements easy to perform”.

When asked if the movements felt natural to perform, the answers were similar to the previous question, as both the standard and anti-symmetrical movements received positive results and the cycling received neutral results, as seen in Figure 20. The symmetrical movements received a mean answer of 6.11 and the anti-symmetrical received a mean answer of 6.22. The cycling received a mean answer of 4.44 with a high variance of 2.78.

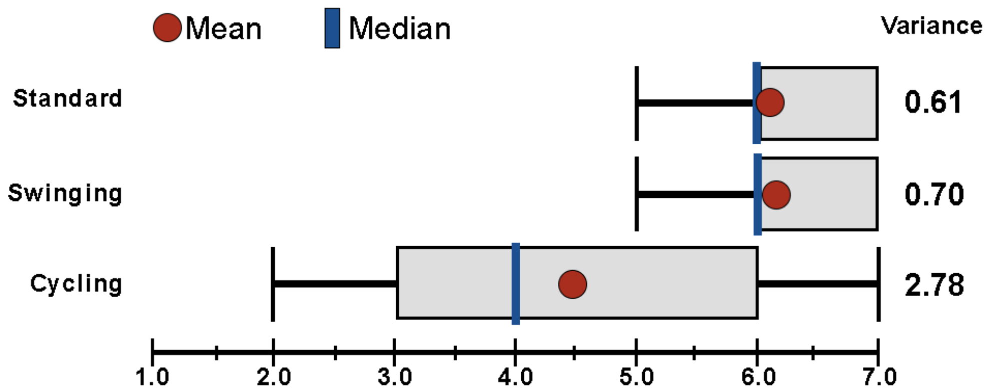

Figure 20: Answers to (2): “The leg movements felt natural to perform”.

3.4.3 Post-test Questionnaire Answers

Following the playthrough of all three versions, the participants were asked to rank them. First, they were asked to “Rate which game you preferred (from favorite to least favorite)” and had to choose one game as the “favorite”, one as “second favorite” and the last as the “least favorite”. Hereafter, the participants were asked to rank the game versions from most-to least exhausting. They had to choose one game as the "most exhausting, one as the "second most exhausting" and the last one as the "least exhausting".

As seen in Figure 21, the anti-symmetrical version was preferred by the majority of the participants, as five participant chose this as their favorite and four as their second favorite version. The symmetrical and cycling version received similar results, with two choosing the symmetrical as the favorite and two choosing the cycling. The cycling version was the least favored version, as five of nine participants chose this version as their least favorite.

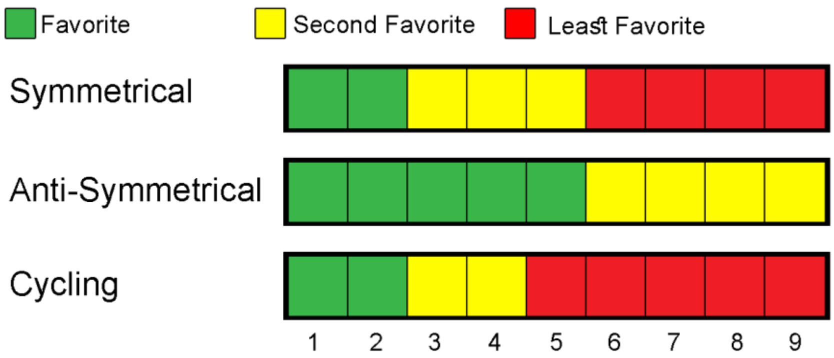

Figure 21: The ranked results of the favored game versions.

When asked to rank the exhaustion rate, the cycling version were rated as the most exhausting by all nine participants. The symmetrical and anti-symmetrical versions received similar results, with anti-symmetrical receiving five favorite votes and symmetrical receiving the last four votes, as seen in Figure 22.

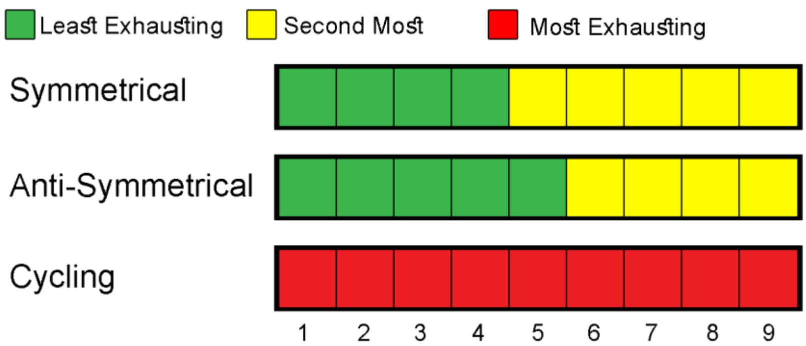

Figure 22: The ranked results of least to most exhausting game versions.

The participants were asked to evaluate to which degree they felt they used both legs during each of the game versions. This was done through a 7-point Likert-scale, ranging from 1: Not at all, to 7: All the time. The answers can be seen in Figure 23. The symmetrical version received a 5.67 mean with a high variance of 2.75. The anti-symmetrical version received a mean answer of 5.89 and with a variance of 1.87. Finally, the cycling version received a mean answer of 6.33 and with all answers ranging from 5 and above on the Likert scale.

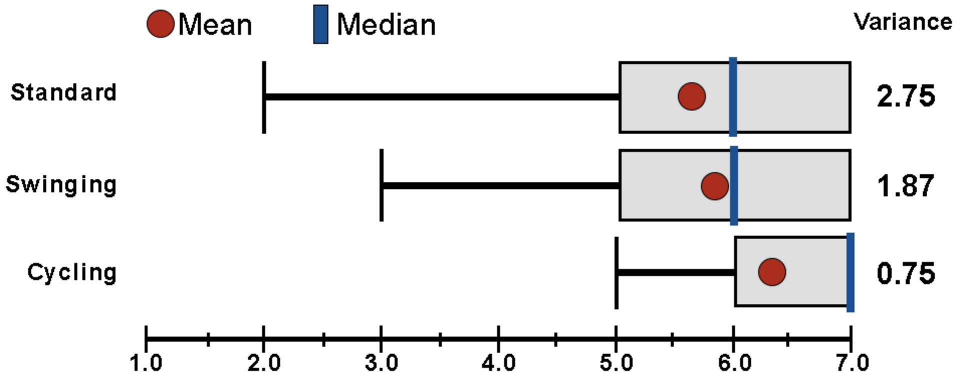

Figure 23: The answers to "How much did you use both legs during the game".

3.5 Discussion

The symmetrical and anti-symmetrical movements generally received positive results. The anti-symmetrical received the lowest scores in the exhaustion rate, but the symmetrical only scored a bit higher. Both versions felt natural and easy to perform by the users. It can therefore be concluded that both versions feel natural to perform, but with the anti-symmetrical movements being the favorite by the participants.

The fatigue experiment showed that the cycling version was a lot more exhausting to complete compared the other versions, and the participants felt the cycling version felt less natural and harder to perform. These results are most likely affected by the high exhaustion rate of the cycling version, but also indicates that it is hard to conduct proper circular cycling movements in the air, which was required to apply the correct force in the cycling version. These incorrect cycling movements resulted in less force applied to the gyrocopter and forced the participants to cycle at a higher pace, in order to achieve the wanted altitude. Some participants still preferred the cycling version and all participants felt they used both legs in this version to a high degree. Therefore, the cycling version should be improved in order to make it easier for the user to understand how to do a proper cycle to apply force to the gyrocopter correctly. By doing this, the exhaustion rate may be lowered in this versions to an acceptable level.

The results from the use of both legs may have been biased because when the facilitator visually demonstrated the three movements, both legs were used. Therefore in the final experiment, it should be clear to the participants that they can decide for themselves if they want to use both legs.

4 Final Experiment

This section describes how we evaluated and tested the different movements applied to the gyropter. The experiment further focused on the usability of the system and the perception of the virtual avatar used in the game.

4.1 Changes to the System

In order to reduce the exertion rate of the cycle game and to help clarify how to correctly apply force, the force system of the gyropter was modified as a result of the preliminary experiment findings. The new version applies force after the user has completed a full sequenced leg motion, and all three versions now apply the same amount of force when one full sequence has been applied. Furthermore, a "flight light indicator", i.e. a light explaining the current status of the leg movement, was included to help the user understand when force was applied, as seen in Figure 24. The light indicator is split into five areas, four surrounding areas and a middle light. The four surrounding areas visualize the current status of the sequence applied by the leg motions. For example, if the participant is playing the cycling game, each piece of the four areas represent one quarter of a full cycle motion. Whenever the participant applies the correct motion, a sequence lights up in a yellow color. When a full sequence is correctly applied, the middle area lights up and a clicking sound is played. This indicates that the user has applied the motions in a correct manner, and force is applied to the gyrocopter.

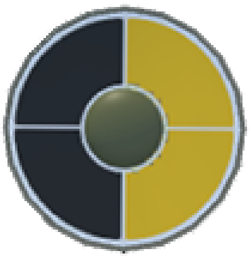

Figure 24: The flight light indicator. In this example, the participant has completed half of the sequence necessary to apply force to the gyrocopter.

4.2 Design and Participants

Besides reducing the exertion rate of the cycling version, another focus in this experiment was to evaluate how much the users applied movement to both legs, in order to find out if the versions encouraged movement of both legs. Furthermore, the anti-symmetrical movements, which are not applicable in a standard MBT session, were compared to the symmetrical version. Finally, the overall usability of the system was evaluated. Therefore, the following focus areas were created:

- The exertion rate of each movement was measured, following the completion of the level for each movement version.
- The amount of movement applied to both legs during each version of the game were evaluated, in order to compare the two anti-symmetrical versions to the mirrored version.
- Evaluating the overall usability of the system and the virtual avatar.

18 healthy participants were recruited at different sites in Aalborg University to the experiment. The experiment was conducted as a within-subject design as all participants were instructed to play through all three versions of the game. The order of play was randomized in a counterbalanced order, in order to remove any carry-over effects.

4.3 Setup

The experiment was conducted in a controlled environment at Aalborg University. The participants were instructed to sit on the edge of a high table when playing through the three versions of the game, as seen in Figure 25. The high table replaced the high metal chair from the previous experiment to remove some external noise. The table added more stability to the seating position, whereas the metal chair would shake or move when the participant applied fast paced leg movements. The participants were equipped with two HTC Vive controllers similarly to the preliminary experiment. A camera was setup to record the leg movements for all participants in each version. The footage was used to check if the participants used one, or both legs to apply the force cycles, how they applied the leg movements and to count how many of each force cycles were applied. The cycles were moreover used to find how much of the cycles were done with both legs, compared to the total number of cycles. Following the completion of a single playthrough, the participants answered questionnaires concerning the exertion rate of the given version through a Borg rating scale, and to rate the leg movements through Likert-scale questions. A post-test questionnaire with focus on the overall usability and the virtual avatar was conducted following the last session of the game. These questions are also rated through Likert-scale questions.

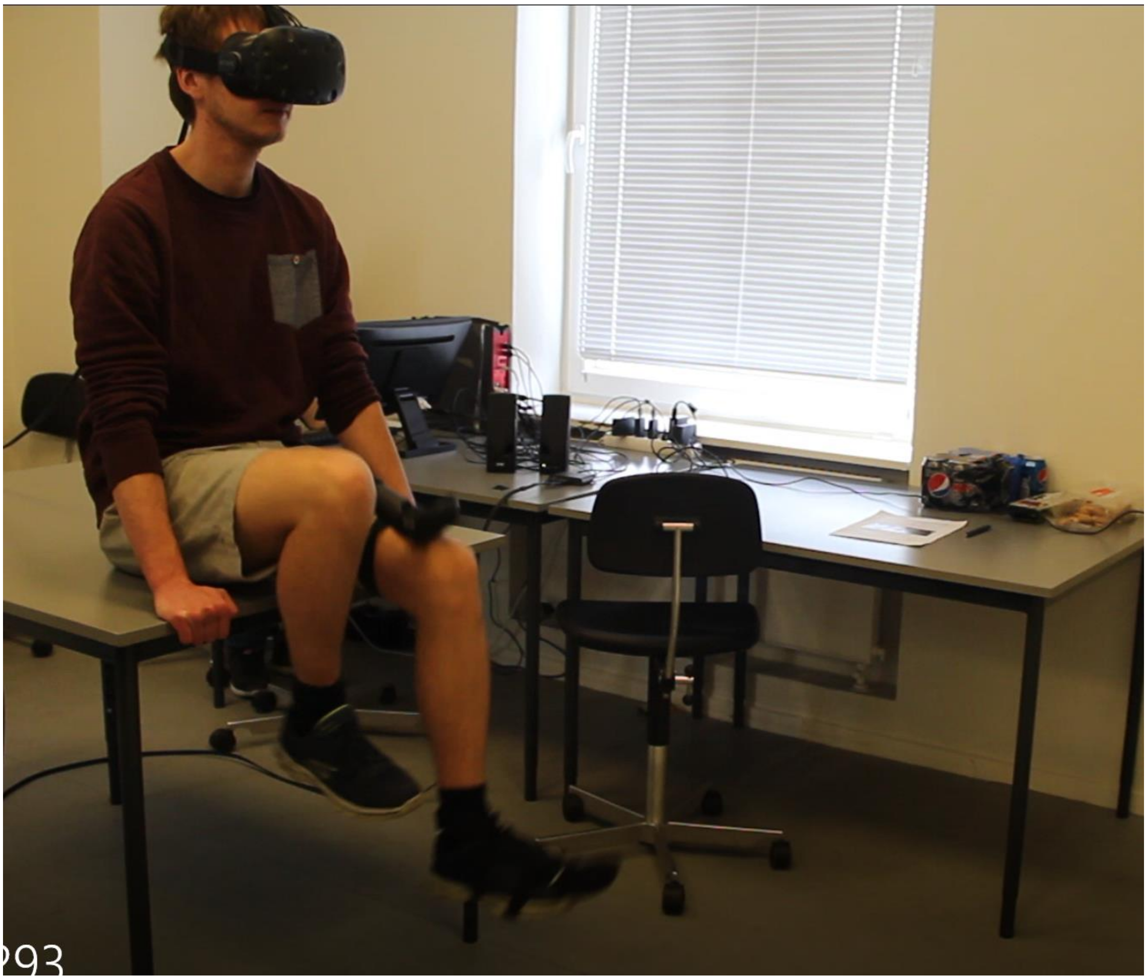

Figure 25: The setup used in the experiment.

4.4 Procedure

The participants were initially instructed to sign a consent form and to read a short description of the test, including instructions to how to control the gyrocopter, the three different movement versions and an overview of the different features in the panel of the gyrocopter. The description further clarified the possibility to play the game using either one or both legs, in order to reduce bias towards one approach. The description can be found in Appendix A. The participants would hereafter equip the controllers and HMD, and be seated in the correct position. Following the introductory part, the participants would complete the level of the game in each of the three versions, in a counterbalanced order. A new level was designed for this experiment and completion took about 3.30 minutes. The checkpoints in this level are positioned in alternating positions, in order to have the participants to look up and down for the next checkpoint. This was done to encourage the users to make use of the helping features in the gyrocopter panel. Following each version, the participants were instructed to complete a questionnaire, in order to get the exertion results while they were still in their recent memory and to get a short break from the game. After all three game iterations were completed, the participants completed the post-questionnaire.

4.5 Results

This experiment was conducted with 18 participants in the age of 21-37 (5 females and 13 males) with an average age of 25.9 years. The participants were mainly students from various educations at Aalborg University. All participants had some, but various, experiences with using Virtual Reality prior to this experiment.

4.5.1 Exertion Rate

The exertion rate was evaluated following each iteration through a Borg scale rating. The Borg scale was used using the same preferences as in the preliminary experiment. The exertion results can be seen in the box plots in Figure 26. The symmetrical and anti-symmetrical versions did not indicate to have a high exertion rate as their respective answered mean value were 9.06 for the symmetrical and 9.56 for the anti-symmetrical version, with 9 being relative to walking slowly. The cycling version however received a mean answer of 13.39, which is about “hard, but manageable” and a median of 14.

Compared to the previous fatigue experiment, with the changes in the force function and the addition of the “flight light indicator” to help visualizing the force applied, the symmetrical and anti-symmetrical versions received almost identical results. Their respective mean value changes were: (1) symmetrical: -0.47 and (2) anti-symmetrical: 0.23. The cycling version had the exertion rate lowered, as the mean value changed with (3) cycling: -0.50. Following each iteration, the participants were instructed to explain if they experienced any discomfort during the level. In the symmetrical and anti-symmetrical versions, two participants experienced discomfort, while 16 did not. In the cycling version, ten participants explained they felt a type of discomfort, while eight did not. The main discomfort types included: (1) strained muscles, (2) sweating under the head-mounted display and (3) sweating in general. No participants experienced nausea in any of the three versions.

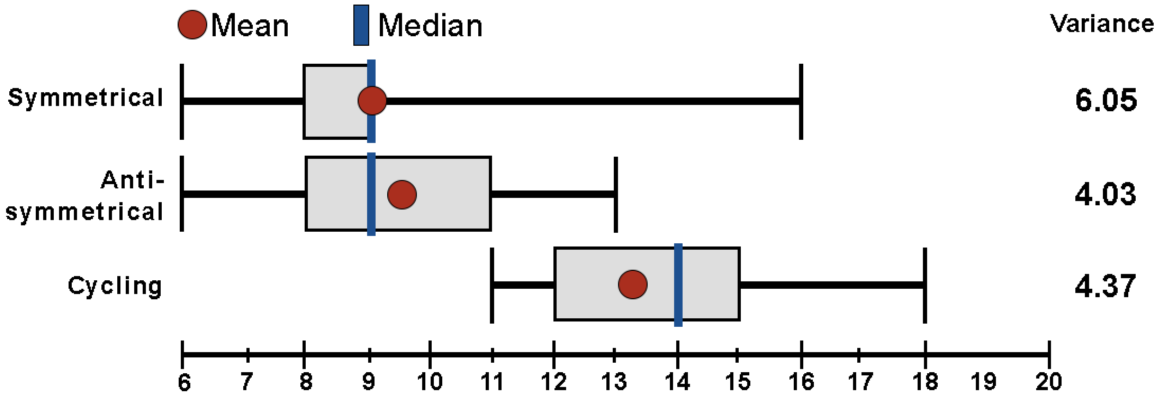

Figure 26: The exertion rate of each of the three version, based on a BORG scale rating.

Following the three iterations of the game the participants were instructed to rank the three versions in terms of how exhausting there were. They were asked to rank the three versions from (1) least exhausting, (2) second most exhausting and (3) most exhausting. As seen in Figure 27, the symmetrical version was chosen as the least exhausting version with 11 choosing this version and 6 choosing the anti-symmetrical version. This corresponds with the exertion rate data, as the symmetrical and anti-symmetrical versions are rated close to each other in the Borg scale for the exertion rate, but with the symmetrical version being less exhausting. The cycling version was ranked as the most exhausting version by 17 of 18 participants, which also corresponds with the results from the Borg scale.

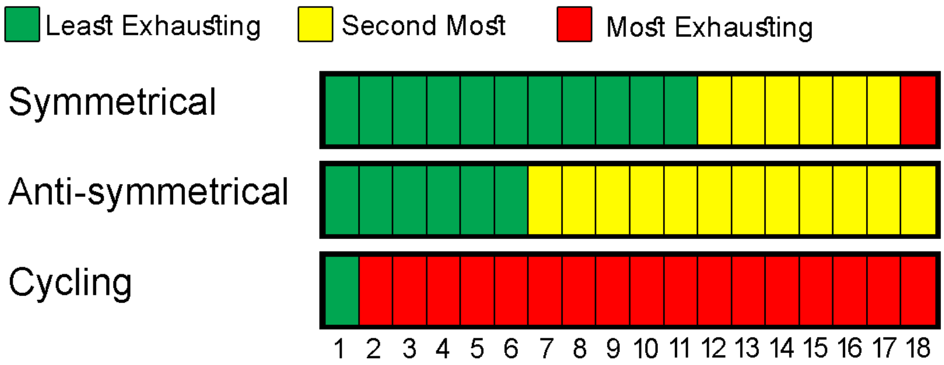

Figure 27: The three version ranked in terms of exhaustion, ranked from (1) least exhausting, (2) second most and (3) most.

4.5.2 Leg Movements

The leg movements of the participants were filmed in order to evaluate the use of both legs during each of the three versions of the game. In each version, the number of completed cycles were counted, and split into either "one leg" counters or "both leg" counters. Full data from the evaluated filmed movements can be found in Appendix B. The results from the data set includes:

- (1) Symmetrical: In the symmetrical version both legs were used overall 92.5% of the time, as 15 of the participants used both legs while applying force all the time, two used both legs during the majority of the cycles and one used both legs in only 8.3% of the time, as seen in Table 1, row (1). It was further noted that three participants would alternate between using the correct symmetrical movements to anti-symmetrical movements in some cases, either in the beginning of the level or when having to apply a high pace.
- (2) Anti-symmetrical: Overall the participants used both legs 88.4% of the time during the anti-symmetrical movements, as seen in Table 1, row (2). Here, 13 of the participants used both legs at all times, while three used both more than half of the time and two only used both in about ⅓ of the time. One participant was noted applying symmetrical movements in the beginning, but changed to the correct anti-symmetrical movements after a short while.
- (3) Cycling: Overall both legs were used 96% of the time as 15 participant used both legs all the time and 3 used both legs more than half of the time. One participant

would only use one leg while applying force once, while using both in higher paced areas. Even though many used both legs, how they used the legs varied. Two participants would apply small circular motions, while two would apply flat swinging motions which looked close to the anti-symmetrical motions. Finally, one participant applied motions that looked similar to running motions.

Since the data is not normally distributed, a Friedman's test was used. The use of both legs for the participants was not significantly different between the three versions, $2(2) = 0.888$, $p > .05$ ($p = 0.6412$).

Table 1: How much both legs were used in full cycles, in percentage.
First line (1) is the symmetrical version, (2) anti-symmetrical and (3) is the cycling version.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
(1)	100	8.3	100	100	100	81.4	100	100	100	100	73	100	100	100	100	100	100	100
(2)	100	100	100	100	89.1	50.6	100	100	77.1	100	100	100	37.4	100	36.1	100	100	100
(3)	100	87.3	100	100	64.8	100	100	77.1	100	100	100	100	100	100	100	100	100	100

Following each version, the participants were instructed to evaluate the leg movements through five Likert Scale questions ranked from 1: strongly disagree to 7: strongly agree. The participants found the leg movements required in the symmetrical and anti-symmetrical versions easy to perform as the mean answers were 6.22 and 6.33 respectively with 17 of 18 participants agreeing in both questions, as seen in Figure 28. The cycling version received a mean answer of 4.37, which indicate the participants did not feel the cycling version were particularly easy to perform.

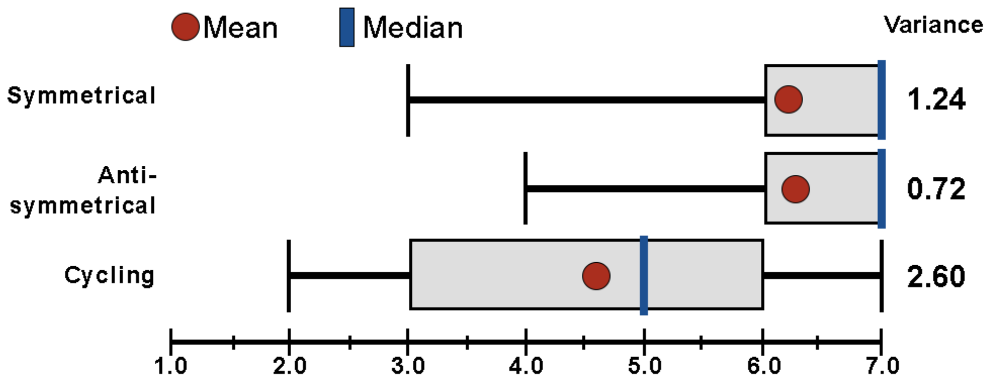

Figure 28: Question (1): “I found the leg movements easy to perform”.

When asked if the symmetrical and anti-symmetrical leg movements felt natural to perform the mean answer was 5.89 for both answers, as seen in Figure 29, which indicates the participants felt these versions were natural to perform. However, the cycling version received mixed answers with a mean of 4.22 and a large variance of 3.71, which indicates not everyone found the cycling movements natural.

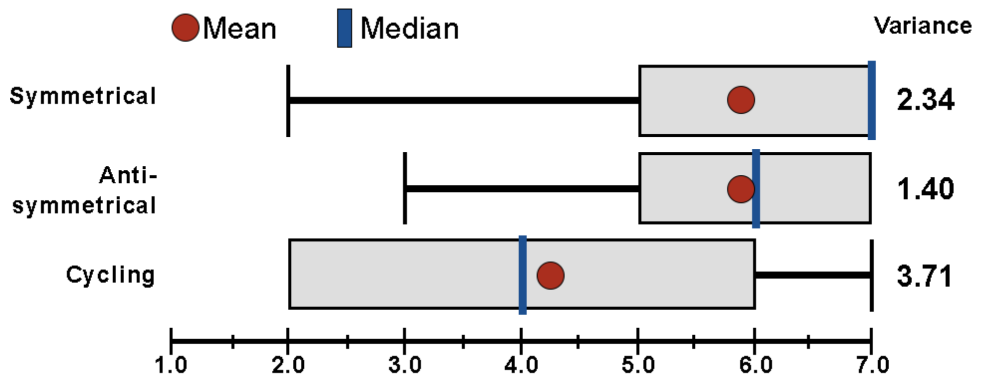

Figure 29: Question (2): “The leg movements felt natural to perform”.

When asked if the leg movements felt consistent with their real leg movements, the symmetrical version received a mean answer of 6.11 and the anti-symmetrical 6.00, as seen in Figure 30. Furthermore, in both versions 17 of 18 participants agreed to some degree on this question. The cycling version generally got positive results as the mean answer was 5.11 and 13 agreeing to some degree.

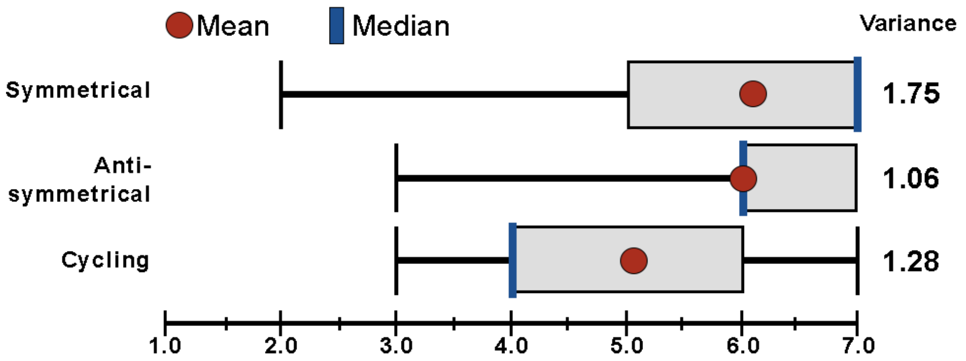

Figure 30: Question (3): “The leg movement felt consistent with my real leg movement(s)”.

When asked if the participants understood how to make the gyropter move upwards, all answer received positive results, as the means answers were: 6.61 for the symmetrical, 6.67 for the anti-symmetrical and 6.33 for the cycling version, as seen in Figure 31.

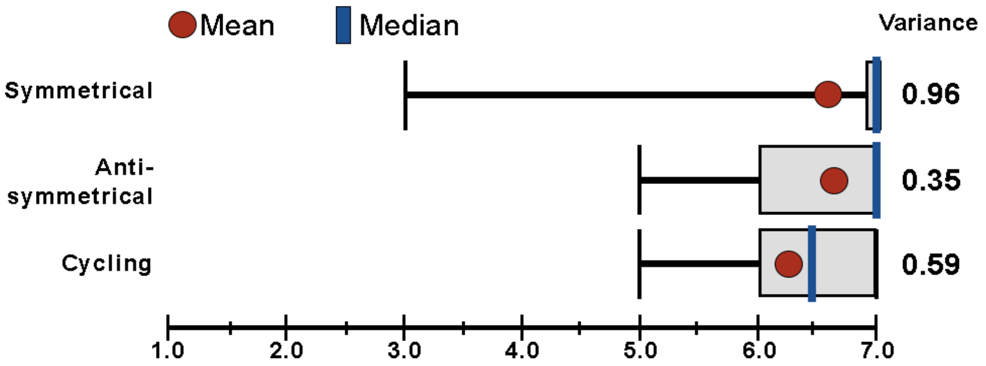

Figure 31: Question (4): “I understood how to make the helicopter move upwards”.

Finally, when asked if it was easy to apply the movements required to make the gyrocopter fly upwards, the symmetrical and anti-symmetrical versions received positive results, as the mean answers were 6.11 for both versions, as seen in Figure 32. The cycling version received mixed results as the mean answer was 4.40 with a large variance of 2.84.

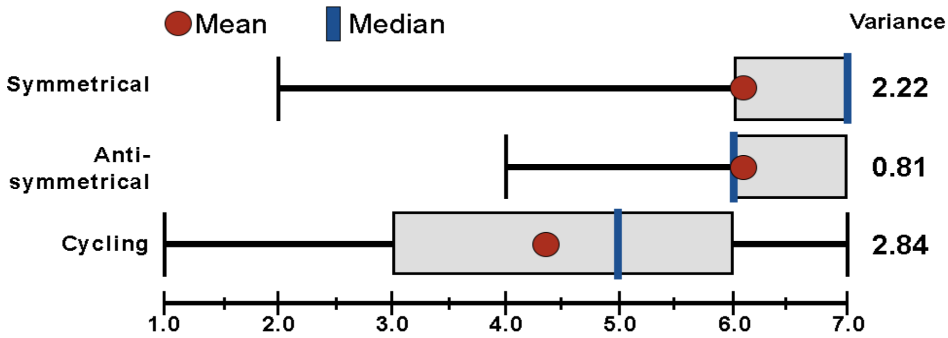

Figure 32: Question (5): "It was easy to do the movements required to fly the helicopter upwards".

4.5.3 Game Data

Following the three iterations of the game, the participants were instructed to rank the games as (1) favorite version, (2) second favorite and (3) least favorite version. As seen in Figure 33, the anti-symmetrical version was the favorite game version, as 11 chose this as their favorite and six chose it as their second favorite. The cycling was their least favorite, with 14 choosing this version as their least favorite game version.

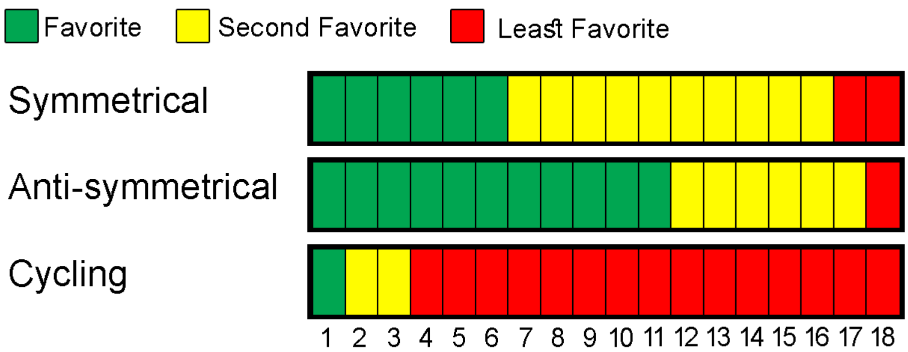

Figure 33: The preferred versions, ranked by (1) favorite version, (2) second favorite version and (3) least favorite version.

During each game version the participants were instructed to hit as many checkpoints as possible throughout the level, with 17 points being the maximum amount of points for one round. As seen in Figure 34, the symmetrical version achieved a mean score of 12.39 and a variance of 8.84. The anti-symmetrical achieved similar results with an average of 12.22 and variance of 10.89, while the cycling achieved lower scores with the mean score being 9.56 and the variance 10.03. Since the data is not normally distributed, a Friedman's test was used. The score differed significantly between the three versions, *2*(2) = 10.522, $p < .05$ (*p*

= 0.0052). Wilcoxon test was used to follow up this finding. A Bonferroni correction was applied and so all effects are reported at a 0.025 level of significance. It appears that the Cycling version had a significantly lower score than the Symmetrical version, $T = 144$, $p = 0.0113$. There was not a significant difference in score between the Symmetrical and Anti-symmetrical versions, $T = 61.5$ $p = 0.9543$.

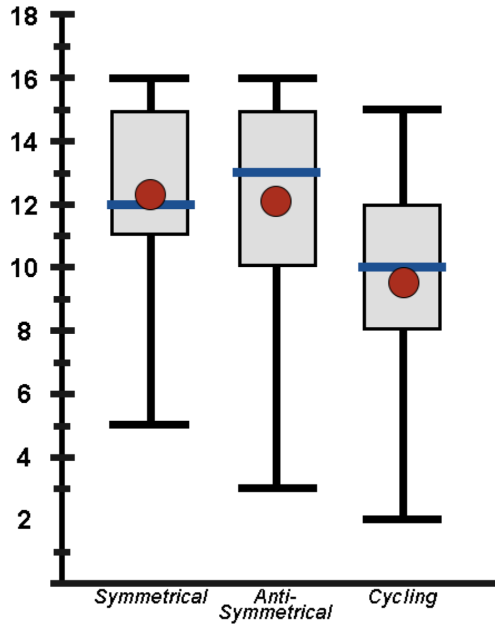

Figure 34: Boxplots of the scores in the symmetrical, anti-symmetrical and cycling game.

Following the three iterations the participants were instructed to answer nine Likert-scale item questions, based on the usability of the system. The answers can be seen in box-plots in Figure 35. The nine questions were: (1) “I quickly learned how to fly the helicopter”, (2) “I was satisfied with the visual feedback of the "flight light indicator"”, (3) “I was satisfied with the audio feedback of the "flight light indicator"”, (4) “ To which degree did you use the altitude meter?”, (5) “I was satisfied with the visual feedback of the altitude meter”, (6) “To which degree did you use the GPS screen?”, (7) “I was satisfied with the visual feedback of the GPS screen”, (8) “ I understood how I was awarded points” and (9) “I was satisfied with the audiovisual feedback from the checkpoints (the yellow circles)”. Question (4) and (6) ranged from 1: Not at all to 7: All the time, while the other questions ranged from 1: Strongly disagree to 7: Strongly agree.

Question (1) received a mean answer of 5.72 which indicates the participants learned how to fly the helicopter. The visual and audio feedback from the "light indicator" received positive results as question (2) received a mean answer of 5.33 and question (3) received a mean answer of 6.33. However, the altitude meter and the GPS screen received mixed answers, as the mean answer of question (5) was 4.44 and question (7) was 4.06, both with a large variance. These mixed answers makes sense as the altitude meter was only used by 3 participants to some degree and the mean answer for question (4) was 2.50. As for the GPS Screen, no participants used it and the mean answer for question (6) was 1.28. All participants understood how they were awarded points as question (8) received a mean answer of 6.67 and the checkpoints received positive audio and visual feedback with a mean answer of 6.11 for question (9).

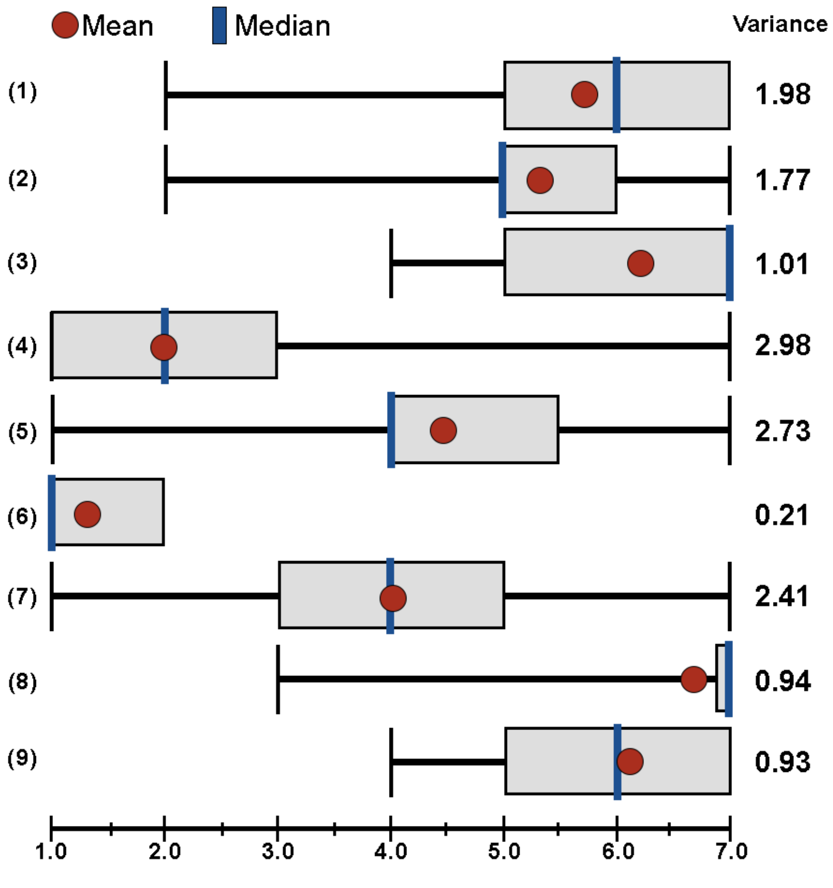

Figure 35: The box-plot answers for the nine usability Likert-scale questions.

4.5.4 The Virtual Avatar

The final part of the post-test questionnaire consisted of four Likert-scale questions with focus on the establishment of body ownership with the virtual avatar [19]. All four questions were ranked from 1: strongly disagree to 7: strongly agree. Box-plots of the answers can be seen in Figure 36. The four questions were (10) “The virtual body felt proportionate to my real body”, (11) “I felt that the movements of the virtual body were caused by my own movements”, (12) “Even though the body I saw might not physically look like me, I felt that the virtual body I saw when I looked down towards myself was my body”, and (13) “The body I saw in the virtual world physically looked like me”.

The participants felt the avatar was proportionate to their body to some degree as question (10) received a mean answer of 5.44 and no participants disagreeing. Therefore, the scaling of the avatar during the calibration phase seems to be working. For question (11) the mean answer was 6.50, which indicate the movements of the avatar were convincing and was caused by their own movements. This was further confirmed as the mean answer for question (12) was 5.56 with only one participant disagreeing. Even though the participants felt the virtual avatar represented their own body, it did not look like their own, as question (13) received a mean answer of 3.83 and six participants agreeing.

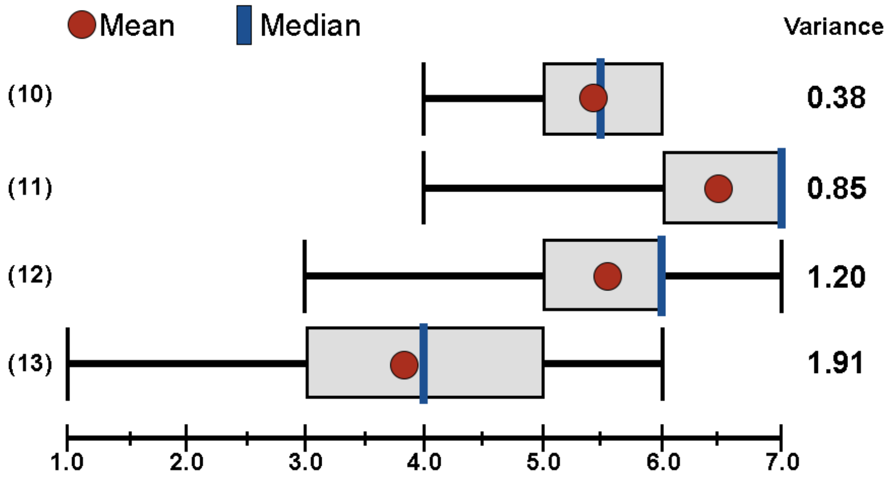

Figure 36: Boxplots answers of the questions regarding the virtual avatar.

4.6 Discussion

The participants used both legs to a high degree in all three versions and there was no significant difference between them. As the three versions applied force through the same system, it would indicate that applying the cycling motions was a lot harder, compared to the other two versions. Therefore it was not the difference in the force input that was applied in the preliminary test that was the cause of the exertion rate, but rather the cycling movements themselves. One reason for the high exertion rate for the cycle game could be the increased amount of movements overall, as the participants needed to lift their legs besides applying the swinging motions. Furthermore, it was noted that the participants used different approaches to apply the cycling motions; some would apply small circular motions and do well in the game, while others would apply very flat cycling motions which did not help applying the force correctly. One reason for this could be that the flight light indicator did not work sufficiently in explaining if the motions applied were correctly. However, in the post-test questionnaire, the participants generally agreed that they were satisfied with the light indicator and they approved of the visual and audio feedback received. So, another reason for the difficulties applying the cycling motion could be that applying cycling motions with the feet in the air without the help of physical pedals is not a movement that is easy to apply naturally and in a stable cycling motion.

In regards to the symmetrical and anti-symmetrical versions, both received a low exertion rate score on the Borg scale, with the symmetrical version being marginally lower. But the anti-symmetrical version was favored by most participants. Furthermore, it should be noted that some participants would change from symmetrical to anti-symmetrical movements within the same level. This could indicate that the anti-symmetrical swinging motions indeed are natural movements, though not significantly more than the symmetrical.

The participants felt they quickly learned how to control the gyrocopter and understood how to apply force to the gyrocopter. They felt it was easy to understand how to apply force in the symmetrical and anti-symmetrical versions, but some had problems understanding how to apply force in the cycling. This was probably caused by the cycling version being exhausting and that the participants had problems applying the correct movements. The participants generally did seem to improve at the games to some degree, but they did not use the GPS screen or the altitude meter when playing. This could indicate that these features were not necessary for the participants to complete the game, though their scores may have been increased if they did use them. Either way, these features were not enough to encourage the participants to look down onto the panel. However, the participants did use the flight light indicator. The participants understood how they received points and were satisfied with the visual and audio feedback from the checkpoints.

The participants generally felt the virtual avatar was proportionate to their real body, though the median answer was between slightly agree and agree. However, this is sufficient to establish sensory acceptance to the virtual limbs. This was further confirmed as the participants felt they were the ones causing the movements of the avatar and felt the body belonged to them. Therefore it seems the visual representation of the avatars worked satisfactory.

5 Conclusion & Future Work

One of the goals of this project was to test if the three movements chosen, symmetrical, anti-symmetrical and cycling, encouraged the use of both legs when playing the game. This was evaluated by counting the percentage of how much the participants used both legs in each game. The evaluation showed that all three games did encourage the use of both legs, as the symmetrical version resulted in 92.5%, the anti-symmetrical did 88.4% and the cycling did 96%.

Another focus of the project was to compare if the anti-symmetrical movements were more natural to perform, compared to the standard symmetrical version. This was done by comparing the use of both legs in the anti-symmetrical versions and comparing them with the symmetrical. Furthermore, the versions were compared by having the participants ranking the versions. This did not show any significant difference between the versions in using both legs. However, the anti-symmetrical version was the favored version. This indicates that the anti-symmetrical swinging movements are at least as favorable to apply as the standard symmetrical. The cycling, however, was not well received and the participants did not find it easy to perform. The symmetrical and the anti-symmetrical version did not seem to be too exhausting to perform. However, the cycling version was significantly more exhausting to perform compared to the other versions. This finding suggests that the cycling version cannot be used for VR MBT, because the patients have to perform these exercises over a longer period of time. To address the issue of the cycling version, a physical pedal could be used where patients could feel some resistance while pushing the pedal. Furthermore, the patients would be guided by the pedal and would perform a correct sequence every time.

The avatars worked satisfactory as the participants felt the movements of the avatar were caused by their own movements. Therefore it can be concluded that the avatar did apply the sensory input synchronously to the expectation of the user and that the limb positioning of the avatar was acceptable. Furthermore, the participants felt the visual representation of the avatar was proportionate to their real body, and felt they were looking at their own body. Therefore, the avatars were able to comply with the requirements for establishing sensory acceptance.

The goal of the game was clear for the participants and they understood how to control the gyrocopter. The game did encourage to use their legs as they tried to reach all the checkpoints throughout the levels. However the GPS screen and the altitude meter were not used by the participants. In a future version these features should be re-evaluated to help the participants perform better in the game.

Overall, it can be concluded that anti-symmetrical movements can be used in the same manner as symmetrical movements in VR MBT for lower-limb amputees.

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Appendix A: Participant Game Description

The purpose of this experiment is to try out three different leg movements to control a helicopter. The three leg movements are: symmetrical swinging, anti-symmetrical swinging, and cycling. The goal of the game is to try to hit the targets floating in the air by using your legs to fly upwards. You will get two Vive controllers mounted to your left leg, one on the foot and one on the thigh. These controllers measure your leg movements.

How to control the helicopter:
Once you're up in the air, the helicopter will move forward automatically. You only control the helicopter's upward motion.

Symmetrical swinging: Move your legs back and forth in a symmetrical manner.
Anti-symmetrical swinging: Move one leg backwards while moving the other forward.
Cycling: Do a cycling motion with your legs. One full cycle pushes the helicopter upwards.

You can decide for yourself if you want to use both legs, or only the controlled legs

Cockpit overview:

1. **GPS screen**:
    a. The red circle on the GPS screen shows where you are on the map
    b. The yellow circles indicate the position of checkpoints
2. **Score screen**:

. Displays the points awarded throughout the level. You get a point when you hit a yellow checkpoint circle.

3. **Flight light indicator**:

. The flight light visualises the current status of the full cycle.
a. One full cycle = upwards force

4. **Altitude meter**:

. The altitude meter indicates the current height of the helicopter. This is indicated by the **red arrow** on the altitude meter
a. The **green arrow** visualises the height of the next checkpoint in the level

If you have any questions, feel free to ask us anytime.

Appendix B: Video Recorded Data

The tables are set up as followed: (1) Participant number, (2) symmetrical, (3) anti-symmetrical and (4) cycling version. The percentages the amount of times the participant did a full sequence while using either both legs or one leg.

Participant 01	Symmetrical		Anti-symmetrical		Cycling	
	Both legs:	100%	Both legs:	100%	Both legs:	100%

Participant 02	Symmetrical		Cycling		Anti-symmetrical	
	One Leg:	91,7 % (66 swings)	Both Legs:	87,3% (55 swings)	Both Legs	100% (52 swings)
	Both Legs*:	6,9 % (5 swings)	One Leg:	12,7% (8 swings)		
	Both Legs:	1,4 % (1 swing)				
	* Swung legs anti-symmetrical					

- Symmetrical: Tried different approaches in the beginning, but ended up using only the tracked leg
- Cycling: Sometimes swung with one leg when doing single cycles

Participant 03	Anti-symmetrical		Symmetrical		Cycling	
	Both Legs:	96,3% (103 swings)	Both legs:	100% (52 swings)	Both legs:	100% (100 swings)
	Both Legs*:	3,7% (4 swings)				
	* Swung legs symmetrical					

- Anti-symmetrical: Used symmetrical swings in the beginning

Participant 04	Anti-symmetrical		Cycling		Symmetrical	
	Both Legs:	100% (56 swings)	Both legs:	100% (91 swings)	Both legs:	100% (97 swings)

Participant 05	Cycling		Symmetrical		Anti-symmetrical	
	One Leg:	35,2% (24 swings)	Both legs:	100% (70 swings)	Both Legs:	89,1% (82 swings)
	Both Legs:	32,4% (22 swings)			One Leg:	10,9% (10 swings)
	Both Legs*:	32,4% (22 swings)				
	* swung the other leg anti-symmetrical instead of cycling movements.					

- Cycling: Used both legs in the beginning, but stopped after a while

Participant 06	Cycling		Anti-symmetrical		Symmetrical	
	One Leg:	100% (103 swings)	Both legs:	50,6% (43 swings)	Both Legs:	42,7% (32 swings)
			One Leg:	49,4% (42 swings)	Both Legs*:	38,7% (29 swings)
					One Leg	18,6% (14 swings)
					* anti-symmetrical swings	

- Anti-symmetrical: Alternated between one and both legs
- Symmetrical: Started using one leg
- Symmetrical: When having to do high pace movements, the symmetrical movements were changed to anti-symmetrical

Participant 07	Symmetrical		Anti-symmetrical		Cycling	
	Both Legs:	100% (98 swings)	Both legs:	100% (86 swings)	Both legs:	100% (100 wings)

- Cycling: Did very small cycle motions, but circular motions

Participant 08	Symmetrical		Cycling		Anti-symmetrical	
	Both Legs:	100% (81 swings)	Both legs:	95,6% (87 swings)	One Leg:	100% (96 swings)
			One Leg:	4,4% (4 swings)		

- Cycling: Did one leg movements when only doing single cycles.

Participant 09	Anti-symmetrical		Symmetrical		Cycling	
	Both Legs:	77,1% (64 swings)	Both legs:	100% (91 swings)	Both legs:	100% (86 swings)
	One Leg:	22,9% (19 swings)				

- Cycling: Cycle motion is closer to a running motion. Not much circular motion

Participant 10	Anti-symmetrical		Cycling		Symmetrical	
	Both Legs:	100%	Both legs:	100%	Both legs:	100%

- Cycling: Very flat cycle motions, not much circular motion

Participant 11	Cycling		Symmetrical		Anti-symmetrical	
	One Leg:	100% (91 swings)	Both legs:	73% (73 swings)	Both legs:	100% (99 swings)
			One Leg:	27% (27 swings)		

Participant 12	Cycling		Anti-symmetrical		Symmetrical	
	Both Legs:	100% (121 swings)	Both legs*:	80,2% (81 swings)	Both legs:	100% (100 swings)
			Both legs:	19,8% (20 swings)		
			* moved both legs in a anti-symmetrical "jagged" motion			

- Cycling: Very flat cycle motions, not much circular motion

Participant 13	Symmetrical		Anti-symmetrical		Cycling	
	One Leg:	100% (61 swings)	One Leg:	62,6% (57 swings)	Both legs:	100% (76 swings)
			Both legs:	37,4% (34 swings)		

Participant 14	Symmetrical		Cycling		Anti-symmetrical	
	One Leg:	100% (19 swings)	One Leg:	100% (73 swings)	One Leg:	100% (71 swings)

Participant 15	Anti-symmetrical		Symmetrical		Cycling	
	One Leg:	63,4% (39 swings)	Both legs:	100% (92 swings)	Both legs:	100% (67 swings)
	Both Legs:	36,1% (22 swings)				

Participant 16	Anti-symmetrical		Cycling		Symmetrical	
	Both Legs:	100% (75 swings)	Both legs:	100% (82 swings)	Both legs:	100% (71 swings)

- Cycling: Small circular cycle motions

Participant 17	Cycling		Symmetrical		Anti-symmetrical	
	Both Legs:	100% (66 swings)	Both legs:	100% (77 swings)	Both legs:	100% (96 swings)

Participant 18	Cycling		Anti-symmetrical		Symmetrical	
	Both Legs:	100% (67 swings)	Both legs:	100% (61 swings)	Both legs:	100% (58 swings)