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Bachelor Thesis

Interactive Visualisation to assess Hand Kinematics

Interaktive Visualisierung um Hand Kinematiken zu bewerten

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Declaration

I hereby declare that I have written the present thesis independently and without use of other resources than those indicated. The ideas taken directly or indirectly from external sources are duly acknowledged in the text. The present thesis, either in full or in part, has not been previously submitted for grading at any other academic institution.

Heidelberg, January 2nd, 2020 ________________________

Erklärung

Ich versichere hiermit, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Hilfsmittel benutzt habe. Sowohl inhaltlich als auch wörtlich entnommene Inhalte wurden als solche kenntlich gemacht. Die Arbeit ist in gleicher oder vergleichbarer Form noch bei keiner anderen Prüfungsbehörde eingereicht worden.

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Abstract:

Development of feasible assessment methods for hand kinematic analysis is of great importance in many clinical applications like physiotherapy and rehabilitation engineering. Motion analysis for kinematic assessments usually requires high end setups involving costly laboratory grade camera systems or similar detectors. Game based setups, using low cost consumer grade peripheral devices like the Xbox Kinect or the Nintendo Wii, promise repeatable and reproducible experiments for assessment. For this thesis a game for hand kinematic assessment was created which uses a Leap Motion Controller as the only tracking device needed. The game was then used to capture and assess ten participants hand kinematics

Zusammenfassung:

Die Entwicklung von durchführbaren Bewertungsmethoden für die Analyse von Hand Kinematiken ist für viele klinische Anwendungen wie Physiotherapie oder Rehabilitationsforschung von großer Wichtigkeit. Bewegungsanalysen für die Bewertung von Kinematiken benötigen für gewöhnlich aufwändige Aufbauten mit teuren Kamera Systemen oder ähnlichen Sensoren. Auf Video-Spielen basierende Aufbauten versprechen unter Verwendung von Endnutzer Peripherie Geräten wie der Microsoft Kinect oder der Nintendo Wii, wiederholbare und reproduzierbare Experimente für die Bewertung. Für diese Arbeit wurde ein Spiel zur Bewertung von Hand Kinematiken entwickelt welches einen Leap Motion Controller als einziges Aufnahmegerät verwendet. Das spiel wurde dann für das Aufzeichnen und Bewerten der Hand Kinematiken von 10 Probanden verwendet.

Table of content

List of illustrations:

Image Sources for Figures 1-8, 14, 19, 23-26 can be found in Appendix B

List of tables:

1. Introduction

"Kinematics is the study of the geometry of motion" - Beggs (1938).
Coined by A.M. Ampère from the greek word "kinema" (movement, motion) - kinematics forms part of classical mechanics, describing movement in a rigid object or a system of rigid objects, irrespective the forces exchanged on the object that cause it to move (Russel et al., 2015). A rigid object is characterised by the invariable mutual distance of any pair of specified points within the object, meaning the object or body does neither change its shape, nor expands or contracts, while still able to change its position with reference to surrounding objects (Whittaker, 1904). A Kinematic analysis is then used to calculate positions, displacements, velocities and accelerations without regard to the forces that govern them (Russel et al., 2015, Whittaker, 1904). Since kinematics allows for the study of geometry of motion, it is often used in the field of biomechanics to assess multi-link systems, such as the human skeleton (Biewener, 2003). The human hand is a complex, multi-fingered outgrowth of the forearm. Its enormous prehensility enables to perform complex grasping tasks which distinguishes the human, amongst other primates, from other species. Without the fine interaction of muscles and tendons that causes the bones to move, creating and using complex tools would be impossible.
Capturing hand kinematics gives an insight in the interactions of this complex motion apparatus and can be used to understand and analyse impairments caused by a multitude of diseases, which often result in disabilities. Therefore capturing sets an analytical basis for assessment. Technological advancements, such as the invention of infrared camera systems, have given the opportunity to capture motion under certain aspects, for later analysis, in a three dimensional coordinate system. These technologies do not only differ in size, price and tracking quality, but also in the complexity of the required software needed to operate them. Lower priced systems like the Microsoft Kinect or the Leap Motion Controller can typically be used in a plug and play style making the use much easier compared to laboratory grade setups involving multiple cameras. Clinical applications such as stroke rehabilitation typically involves the patient in exercising different movement patterns while being supervises by an expert. Studies have analysed the impact of using video game based therapy, involving a motion capturing system, by comparing them

against conventional therapy (Jung et al., 2018, Rathinam et al., 2018, Tarakci et al., 2019). Their results show the benefits of using video game based therapy as an alternative to conventional therapy, by challenging the patient to perform intensive movement practice in an encouraging game-like environment. High dropout rates and low compliance towards conventional movement practice are ascribed to the lack of motivation missing by exercise sheets used in conventional post stroke therapy (Zondervan et al., 2016). Additionally the amount of one-on-one exercise training with a therapist in none home-based meetings can be heavily reduced due to the portability of video game based therapy. Furthermore, video game based therapy enables to repeat exercises with little to no change in the setup and therefore allows to perform the large number of repetitions needed to increase the success of rehabilitation.

For this work, an interactive visualisation was created as a game playable on both Windows and Linux operating systems. The game tracks the user's hand while playing and allows via different pinch grip exercises the assessment of the subject's hand kinematics. A Leap Motion Controller (LMC) was used as the game's main input and is further used to track the user's hand(s).

The second chapter will describe the experiment that was performed to capture and assess hand kinematics.

The third chapter will explain the game's functionality and how recording was made possible.

1.1 Leap

The Leap Motion Controller (shown in Figure 1) is an optoelectronic infrared USB peripheral device, developed by the American company Leap Motion. Its two monochromatic infrared cameras support a almost hemispherical interaction area as can be seen in Figure 2.

Figure 1: Showing the internal structure of the Leap Motion Controller

Within this area hand movement is tracked by the closed source Leap Motion Software, with an overall average accuracy in the sub-millimetre spectrum (Weichert et al., 2013). Its comparatively low cost and free to use software allows tracking without the use of markers, making the Leap attractive for motion tracking. The via Assets provided support for the Unity and Unreal Engine makes the LMC an appropriate device to develop a low cost game setup to capture and assess hand kinematics. Unlike other similar technologies, like the Microsoft Kinect or the Nintendo Wii, the LMC does not create a depth map but rather *"applies advanced algorithms to the raw sensor data"* - Leap Developer Blog.

Figure 2 : Illustrating the interaction area of the LMC

Furthermore, the LMC offers an additional head-mount support allowing the peripheral to be used as an addition for a virtual reality (VR) device. The LMC misses sensors that capture its own movement. Mounting it to a VR-device can provide this information based on the captured movement data of the VR-device.

Figure 3: Illustrating a possbile head-mount for using the LMC with a VR-Device

1.2 Unity3D

Unity is a software development environment specifically designed to create video games. Unity's debut release was in 2005 by Unity Technologies, as a Mac OSX exclusive game engine. At present it supports up to 25 different platforms including Windows and Linux operating systems. Although Unity uses a proprietary Licensing based on a subscription model, a free license can be obtained either for personal use or for smaller companies with less than 100.000 US-Dollars in annually sales. Unity supports two and three dimensional video game design and supports the creation of VR-games (Unity Technologies). Since Unity, unlike the Unreal Engine, offers a stable Linux build via the Unity Hub, a version- and project manager, Unity3D was preferred over the Unreal Engine for the development of the game. The game for this thesis was created using a free license for version “2018 (64-bit)”.

2 Data Collection

2.1 Introduction

The primary goal of this data collecting experiment is to show the game's ability to assess subjects' hand kinematics in terms of the pinching ability, defined as the ability to perform a pinch grip as seen in Figure 4.

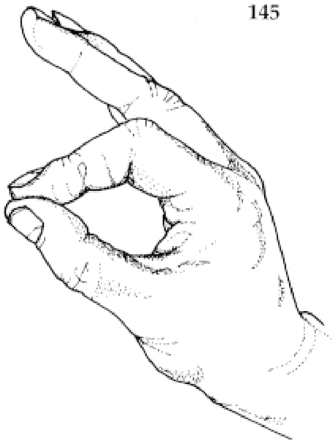

Figure 4: A pinch grip

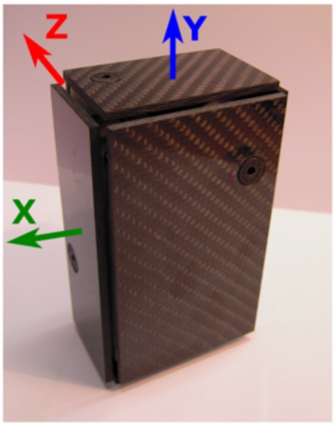

Figure 5: The iBox

To assess the performance of a pinch grip, the experiment records the position of the hand joints and finger tips, as seen in Figure 6, in Unity3D world coordinates. Furthermore the pinch strength, defined in Leap's Application Programming Interface (API) documentation as the holding strength of a pinch hand pose is recorded (Leap API Documentation for V2, 2019) . The pinch strength was then compared against data generated by a study that analysed force exchange during object grasping and manipulation using an iBox (see Figure 5) based setup (Martin-Brevet et al., 2017).

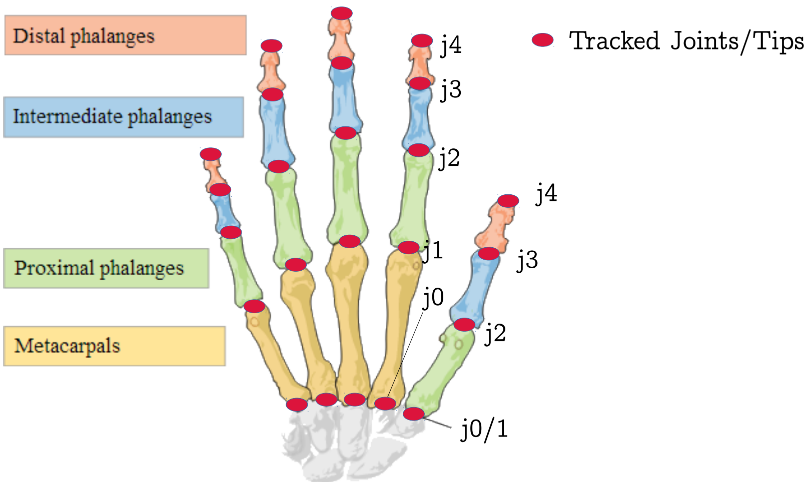

Figure 6: Showing the bone structure of the human hand

2.2 Methology

2.2.1 Participants

Ten participants, aged 20 to 26, volunteered to take part in the data collection and gave written informed consent prior to the experiment. All participants were able to perform a full pinch grip and therefore deemed as healthy without any impairments affecting their dominant hand. Nine out of ten stated to be right handed while only one was left handed. This reflects the estimated 10-15% of left handed people in the overall population (Porac et Coren, 1981).

2.2.2 Equipment

A LMC was used in order to capture and record the subjects' hand kinematics. Due to its Linux compatibility, Leap Tracking V2 with the Leap Motion Software Development Kit (SDK) v2.3.1 was employed for the present study. Prior to recording, the Leap Motion Controller was calibrated with the internal software re-calibration tool to a value of 94 using a cleaned mirror. As can be seen in Figure 7, connected via USB 2.0 and using a 60Hz laptop monitor, latency is below 100 milliseconds and interaction is therefore considered instantaneous (Miller, 1986).

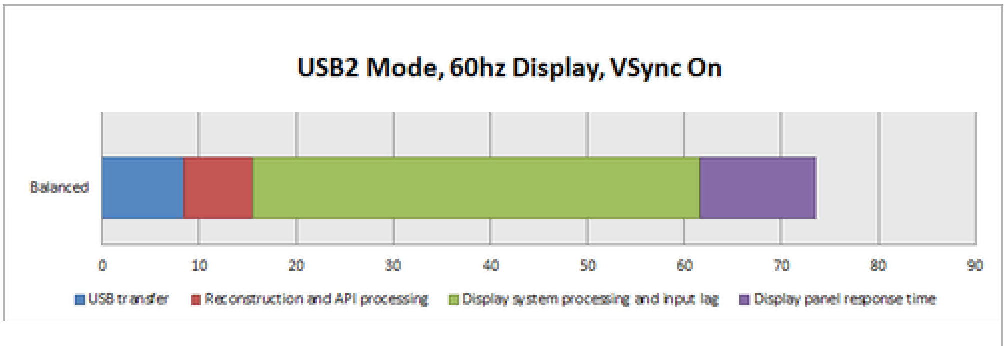

Figure 7: The approximated latency for interaction with the LMC

All data was then collected using only the LMC and the hand kinematics game. The game was run on a Laptop operating on Ubuntu 18.04, due to better mobility of the setup, as shown schematically in Figure 8. For easier access the LMC was positioned slightly to the right side of the Laptop for right-handed participants and vice-versa for the left-handed participant.

Figure 8: The schematic setup for right handed participants

2.2.3 Protocol

Prior to the data collecting experiment the subjects were asked to state their dominant hand. Furthermore, subjects were asked to lift a pencil using only two fingers in a pinch grip fashion to determine if they are suitable for the experiment. Participants were not given a rehearsal trial but were shown a quick demonstration (play-through) of the game to ensure that the tasks were fully understood. Participants' captured data was anonymised by using an identification number followed by the trial number. Each participant was given three trials. Each trial consisting of playing both levels. Lastly all types of accessories, mainly smart watches and wristbands, were removed to avoid external infrared light sources and to minimize reflection.

2.2.4 Recording and (Post-) Processing

After setting up the Leap Motion Controller in an appropriate distance to the participant and the Laptop, with the Leap Motion Controller facing upwards, each participant then played the game three times and for each trial data was acquired and stored, specified for each level, in a comma separated value file. Table 1 shows an exemplary window view of the recorded data. Verbal feedback was given to the participants to facilitate strategic decisions as where and how to grab an object in order to reduce obstruction of the Leap cameras view towards the gripping fingers. Timestamps were generated by calling Unity3D's T*ime.timeSinceLevelLoad()* function that returns a float value representing the seconds since the level was loaded in real time (Unity API, 2019). The first Timestamp is then given as the exact moment, in seconds since the level was loaded, the hand is detected by the LMC, meaning that nothing will be stored in the recorded file if there is no hand present. Using this technique gains the advantage of little to no post processing in terms of removing blank records. In one trial the LMC detected and mislabelled a right hand as a left one after the hand was overturned. Recorded files were cleaned by removing row data if the Boolean value, indicating if the tracked hand is a right one, does not fit to the stated dominant hand of the participant. If necessary, timestamps were later shifted using a lambda function, by subtracting the minimum value of all timestamps for each individual timestamp to ensure the first record start at 0.00s. Acquiring data about the current pinch is done by recording the pinch strength that is given as a float value between 0 (no pinch) and 1 (full pinch). Grabbable objects in the game are designed to have similar dimensions in terms of thickness and therefore a pinch strength value of roughly 0.60 triggers the grasping of an grabbable object within reach of the virtual hand. As said, the recorder also saves a Boolean value stating if the recorded hand is a right hand. Skeletal tracking is implemented and hand joints are tracked based on their position in Unity3D world coordinates either as a vector3 or with separated x, y and z coordinates for each joint, making analysis easier when switching the programming language for data analysis to Python3. Because Unity, unlike Leap, uses a left hand coordinate system, captured z coordinates have to be multiplied by -1 to compensate this difference.

2.3 Results

This section presents the outcome of the data collection process.

An inverse correlation between the pinch strength and the distance between the index and thumb finger tips is existing as can be clearly seen in Figure 9. Moving the index and thumb finger tips closer to each other results in an increasing pinch strength. Because Leap uses closed source software it can only he hypothesised that this distance serves as the main indicator for the pinch strength. Another interesting observation that can be seen in Figure 9 is the distinction of the gripping phases. The left-handed subject was able to finish the level using only the minimum required grasps. This can be ascribed to the subject's stable hand movement and meticulously following along the verbal feedback, as to grab pins on its ends rather then its center as well as trying not to obstruct the LMC's view. Figure 10 shows the same analysis for a right-handed subject. Although the participant finished the level faster then the left-handed one, an additional grasp was needed to properly place the pins. Depending on the selected main criteria for assessment this could be rated worse than the trial represented by Figure 9. In any case technical limitations and unstable tracking behaviour of the Leap's API has to be considered when assessing a trial.

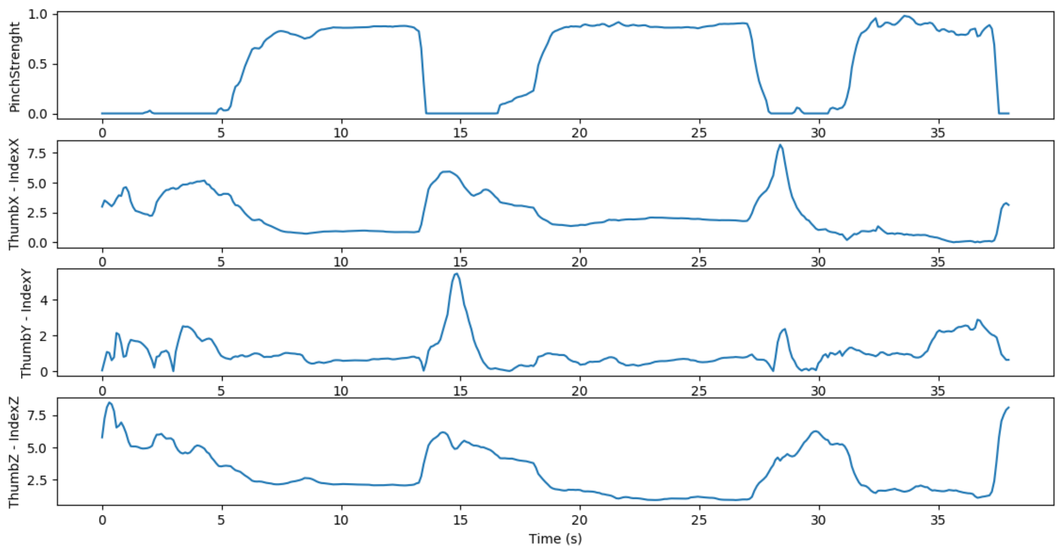

Figure 9: Showing the pinch strength and the distance between thumb and index finger tips for each axis in the course of solving the second level. Left-handed participant

In a best case scenario additional grasps are superfluous, since the levels are designed to be solvable by using the intended and advised strategy. But if the LMC's view towards the fingers is obstructed by e.g. the palm, position of fingers and the current pinch strength, is assumed on previous observations (Leap Motion Blog, 2019). This can often lead to a change in the pinch pose, meaning the object is dropped and needs to be re gripped.

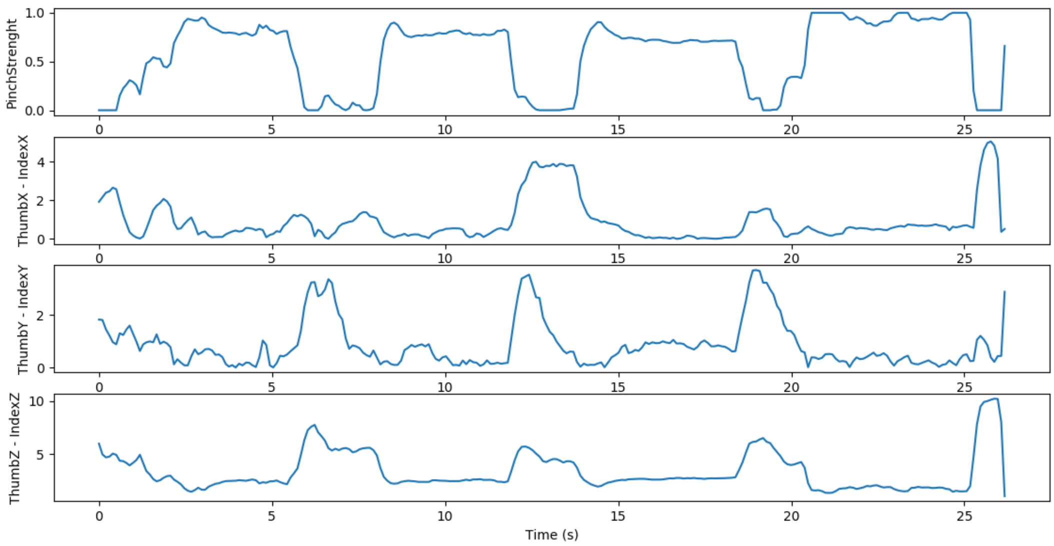

Figure 10: Showing the pinch strength and the distance between thumb and index finger tips for each axis in the course of solving the second level. Right-handed participant

Similar to the Nine Hole Peg Test (NHPT), the overall used time for solving (a level) can be used as an assessment criteria (Earhart et al., 2011). As can be seen in Figure 11 participants tend to better their performance in terms of used time over the course of the experiment. Participants with little to no prior video game experience tend to be among the slowest. Concurrently they were able to decrease their time score the most in the second and third trial in level two. A correlation between frequent video game use – especially first person shooter (FPS) games – and an improvement of the spatial cognitive functions has been found by Spence and Feng (2010) and might be influential on the participants' scores. This suggests that the main reason for the large discrepancy in the inter-participant time scores and the significant decrease in the overall used time for each participant, in the later trials, might not be primarily influenced by the difference in the dexterity, since all participants were deemed healthy, but is rather ascribed to the participants' ability to adapt to the gameplay such as playing the game in a fashion that facilitates an optimal tracking. The data for the first level does not directly corroborate the trend found in the second level regarding the decrease in the time scores in the later trials. It can be seen that the used time actually increases for the last trial. Observing the participants while they played suggests their encouragement of trying to beat not only their own best time, but also the one of the others. This was typically happening in the third trial, after participants were used to the challenge and already had been given a second trial, which most likely already led to better their initial performance. Participants then became less risk adverse, in terms of movement velocity, which often resulted in a sloppy stacking in their third trial, leading the box to fall off.

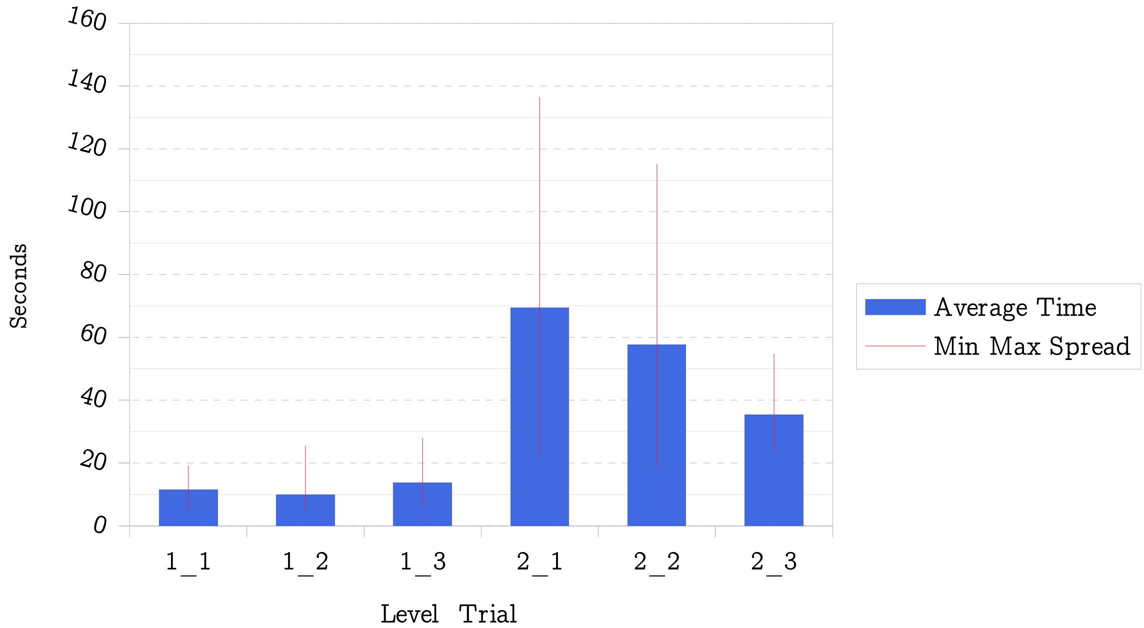

Figure 11: Overall time for solving a level with regards to the spread between the longest and shortest finish time

The first level can be interpreted not only as a tutorial but also as a single pinch grip exercise. This allows the data to be compared against the analysis of force exchange during a pinch grip as reviewed by Martin-Brevet et al. (2017) using an iBox setup. Besides being equipped with an inertial measuring unit, an embedded electronic board to measure its accelerations and rotational velocities, six load cells are used to measure the force applied normally to the iBoxs six faces. Figure 12 shows the force applied to the front and rear side. The applied force increases in the beginning until the bottom force sensor is unloaded (when its force signal decreased below the threshold of 3.4N) then plateaus for a certain amount of time, defined as the holding phase, and decreases rapidly after the iBox is placed back on the table. Martin-Brevet et al. (2017) stated that the gripping forces continued to increase significantly in the lift-off phase then decreased to a lower level while holding the iBox mid air. Since holding requires a force at least equal to the weight of the iBox, the peak in the lift-off phase could be ascribed to an unconscious adaption to physical feedback given by the weight of the iBox.

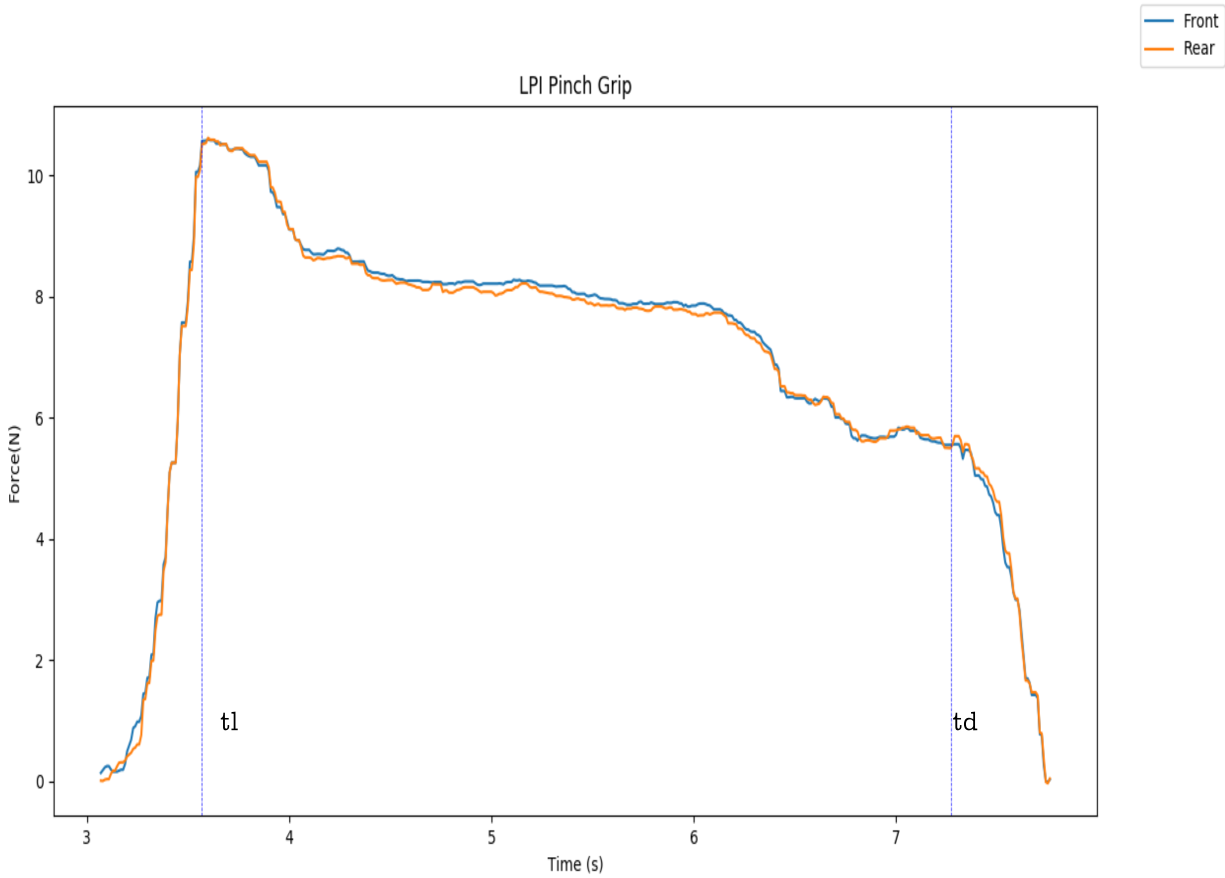

Figure 12: Force exchanged on the iBoxs front and rear side during a pinch grip. tl - onset of lifting , td – time of deposit

Figure 13 shows the pinch strength during the first level for a right-handed participant, who only needed one grasp to complete the levels objective. Similar to Figure 12 the pinch strength rises above the required threshold of approximately 0.60 that triggers a pinch grip, while shortly after, plateauing for the placement procedure - a translation and holding task - of the box.

Most likely, due to lack of physical feedback, the decreasing pinch strength, at the end of the exercise is more sudden compared to grasping an existing physical object, as shown in Figure 12. Contrary to the peak shown in Figure 12, there is no significant peak of the pinch strength detectable when performing a pinch grip of the a virtual cube as seen in Figure 13. This could be ascribed to the lack of physical feedback as e.g. the non existing weight of the virtual object. In general most participants were paying close attention to the colour of the objects, that is used as visual feedback and changes if the object is gripped, while then not further decreasing the distance between index and thumb finger. This was an unexpected observation that shows that visual feedback can, at least to some degree, replace physical feedback.

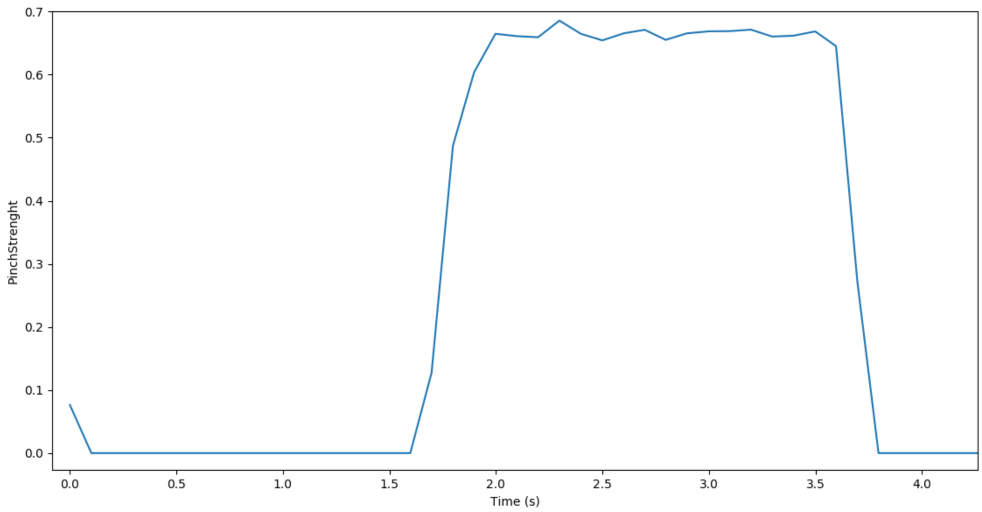

Figure 13: the pinch strength during the first level of a right-handed subject

The overall feedback given by the participants showed that the experiment was well accepted and did not trigger the feeling of a clinical examination. If participants had seen the time scores of other participants a competitive feeling emerged that had a two-sided effect. On the one side, participants were highly motivated to perform as good as they could while on the other side, some participants overestimated their skills failing e.g. to stack the box properly in level one and having to re stack the pile. This effect is one of the reasons for the increasing time over the course of three trials for level one as can be seen in Figure 11. In only one trial the game broke to the point where a pin was stuck on the edge of the interaction area and the trial had to be reset by restarting the level. Data recording has shown to be consistent, using the custom made recorder, for both left- and right-handed subjects.

2.4 Discussion

The experiment showed the possibility of using a video game based setup combined with a LMC to assess hand kinematics. Tracking can be done from within the game using the Leap API instead of having to use a listener running in background connected to the Leap Web socket. The game has shown to be capable of tracking left and right hands (even simultaneously) as exemplary seen in Table 1. The pinch strength can be used as an indicator of the current pinch pose, but not as an actual representation of the strength acted upon the pinch pose, due to it being measured most likely by the distance between index and thumb finger instead of being measured by the actual force exchanged. Since the pinch strength is a unitless measurement, its name can be misleading. The setup proved to be reliable and provided reproducible and repeatable exercises for each participant making the data comparable not only inter-participant but also inter-trial. Each participant was deemed healthy and was able to perform a pinch grip in real life, meaning that there should be no significant difference in their dexterity. Nevertheless some participants finished the levels in a fraction of the time needed by others. As can be seen in Figure 11 the spread is very large and time scores might be heavily influenced by the participants prior video game experience. The spread could be reduced by giving the participants a training phase. Kinematics of the later trials might be biased by the participants trying to perform the tasks in a fashion that facilitates tracking rather than their intuitive way of how they would grasp an object. Therefore the overall time needed might not mainly depend on the dexterity of the participant but also on the quality of the tracking. Future setups should either try to compensate the difference in spatial cognitive performance by using a VR-setup which gives the participants a more equal initial skill set, or allow the participants an additional training phase to get used to the gameplay.

3 The Game

3.1 Introduction

As part of this thesis a “Hand Kinematics Game“ was created and used to capture subjects hand kinematics using a LMC as its main input source.
The game was developed on a 64Bit Windows machine running Unity3D 2018.4.11f1. Its main purpose is to capture and assess hand kinematics while performing pinch grip exercises. Two levels were designed with increasing difficulty. Each level uses a timer stating the overall past time since the level was loaded. The first level was designed as a representation of a single pinch grip exercise and is solved by properly stacking a cube on top of another. The low difficulty furthermore promotes a quick adaption to the gameplay. The second and more difficult level challenges the user to reposition three pins into their corresponding hole and therefore can be seen as a representation of the NHPT. While playing the game visual feedback is given to the user with the goal of replacing the missing physical feedback. A meter, as seen in Figure 20, is used to display the current pinch strength of the grabbing hand.

3.2 Assets

“An Asset is a representation of any item you can use in your game or Project. An Asset may come from a file created outside of Unity, such as a 3D Model, an audio file, an image, or any of the other file types that Unity supports” - Unity Manual

Some elements used in the game are given by the Leap Motion Core Asset Pack (Leap Motion, 2015), which constitutes a basic framework for Unity game development. The asset pack gives important and needed scripts, like the “handcontroller” script that is attached to the “HandController” prefab (prefabricated game object), which represents an anchor point for drawing the hands. In other word, this prefab serves as a virtual LMC and playing the scene will cause any detected hands by the physical LMC to appear relative to the virtual LMC. Unlike the proprietary Leap backend software that can only be accessed via the API, assets and prefabs can be extended and modified as needed, while still providing full API access. Different kinds of hand models, with and without arms, robot like hands, humanoid hands and more abstract ones are are also made available by this asset pack. It shall be noted that this asset pack is outdated at the time of submitting this thesis and newer unity asset packs are available. Nevertheless this asset pack was sufficient as a framework to develop the game and upholds the advantage over newer asset packs of being fully compatible with the Leap Motion Tracking v.2.3.1 SDK, which is the latest SDK that supports Linux. Newer versions mainly focus on VR-development and provide an interaction engine allowing to use and customise the UI-Layer of the project to increase interactivity. The used asset pack does not contain the needed Linux plugins. A custom Linux version of the standard Windows LeapC libraries defining a C-style API have to be made available for the assets. These libraries are given in the SDK as a plugin and have to be manually inserted into the project settings. Another used asset pack was the ProBuilder2, which is a combination of a 3D-modelling and level-design tool optimised for the creation of simple geometries that can not be created using Unity3Ds default 3D model builder. The tool was used for creating the holes in level two, which are actually cubes with the pin hole removed. The ProBuilder2 tool allowed to edit the collider in a way that the default box collider also contains a hole the same size as the cut out in the texture. The last used asset is TextMeshPro, a powerful yet flexible text rendering solution that replaces Unity's default UI- text and text mesh and allows to customise layout and formatting of UI elements.

3.3 Level-Design

Level-design follows three core principles:

First: The visible areas shall also be reachable.

Second: Level tasks have to be repeatable and reproducible pinch grip exercises.

Third: The origin of Leap's right hand sided and Unity3D's left hand sided coordinate system have to be the same.

3.3.1 First: The visible areas shall also be reachable

Both scenes use a single static main camera, approximately depicting the users point of view. The area shown by the main camera is set equal to the LMC's interaction box, that is within Leap's interaction area as shown in Figure 14.

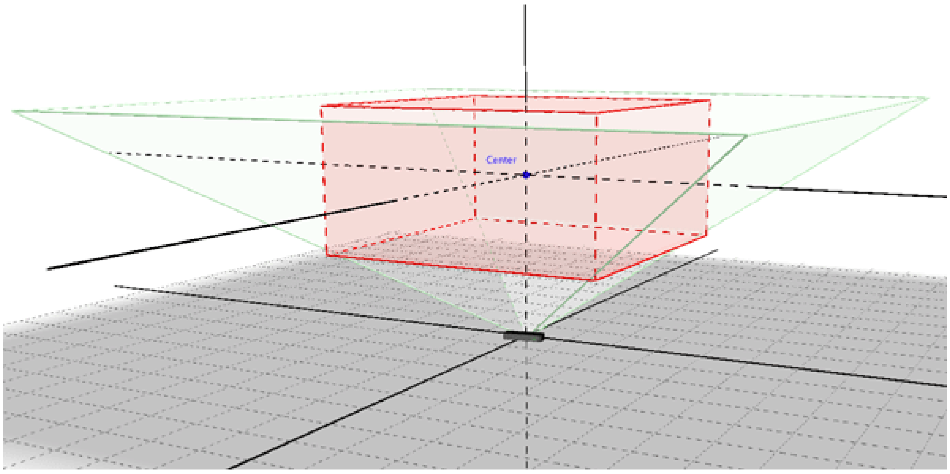

Figure 14: The interaction box enclosed in the interaction area

This ensures that the user can interact within the visible and no visible areas are unreachable. Hand models appear to have a more robust behaviour closer to the LMC's interaction box center than on its edges. Therefore interactive objects either spawn or are positioned reachable by the hand which stays close to the interaction box center.

3.3.2 Second: Level tasks have to be repeatable and reproducible pinch grip exercises

Both levels are designed with increasing difficulty to challenge the users dexterity. The first level requires the user to pinch grip a small cube and place it carefully on top of another one. The level is completed if the cube is no longer grabbed and stays on top for three seconds. Previous iterations of the level required to stack up to four cubes of equal size, requiring very precise stacking for each. Due to technical limitations, such as colliding with the pile when tracking is lost, this design was deemed to be too difficult and was therefore not further pursued. Positioning the cube still requires precision due to it being exposed to gravity given by Unity3D's physics engine, meaning that placing the cube on the edge could cause it to fall off. Hence the use of a three second timer. Due to its lower difficulty, compared to the second level, it can be considered as a introduction or tutorial for the user, to get used to the game mechanics.

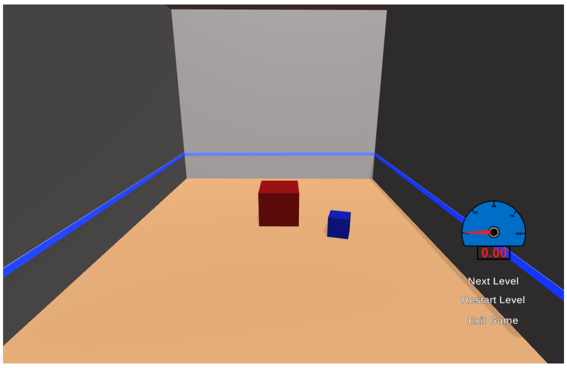

Figure 15: Level 1 initial

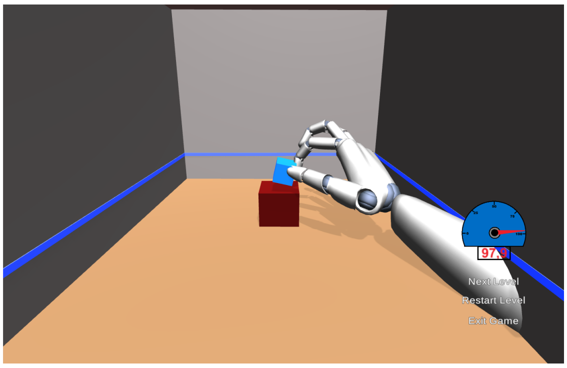

Figure 16: Level 1 about to be solved

The second level is a partial representation of the NHPT, which is commonly used to measure finger dexterity for various neurological diagnoses due to its high test-retest coefficients combined with its simple low-cost yet efficient design for kinematic assessment across a high age range (Wang et al., 2011). The level differs by using only three pins and assigning pins to holes by colour coding the items. Initially one hole is unoccupied and two pins are standing upright in the incorrect hole, while the green pin lies flat on the ground. This sets a sequence of grabs, required to place the pins in the correct hole, while extending the task with a palm rotation of roughly 90 degrees in order to properly place the green pin. Setting this sequence and encouraging the participants to follow allows the trials to be comparable not only by measuring the overall past time, but also by the total amount of grips.

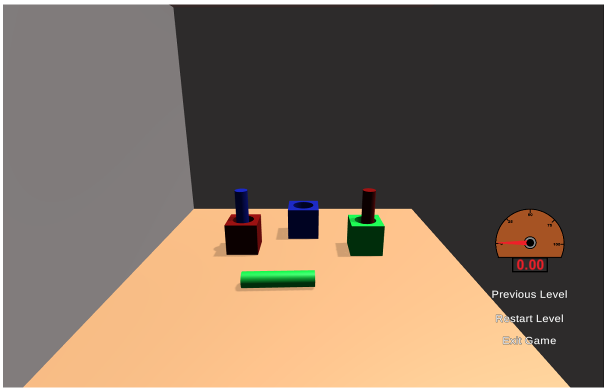

Figure 17: Level 2 initial

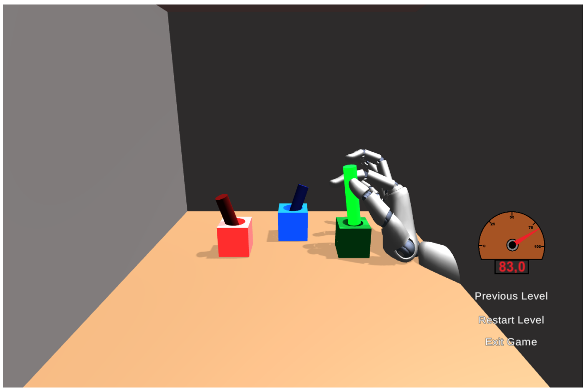

Figure 18: Level 2 about to be solved

3.3.3 Third: The origin of Leap's right hand sided and Unity3D's left hand sided coordinate system have to be the same

This is ensured by setting the x, y and z coordinates of the virtual LMC to (0,0,0) in Unity3D world coordinates. The reason for using this principle is to allow future work based on the game, to use a different data recording technique, even with newer API versions, without having to use a mapping for coordinates in a post processing step.

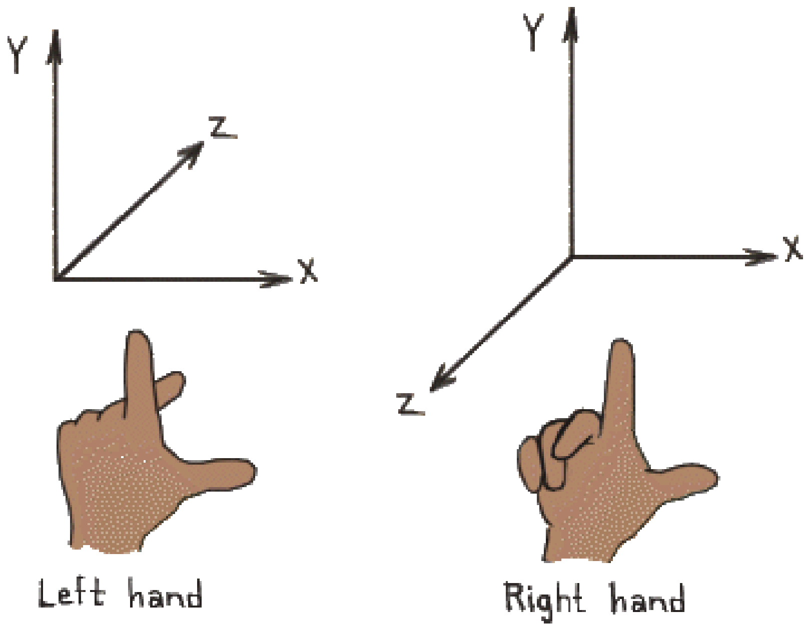

Figure 19: Left handed and right handed coordinate systems, the arrows indicate the positive direction

3.4 Making the game robust

Starting out as a simple single scene, that could only be run from within Unity3D without any stand-alone build options, new features were continuously added to either serve the purpose of making the game more robust or extending its functionality. The most important feature, at least in the beginning, was to add a menu system allowing to skip levels or reload them from within the current scene. This is done by scripts invoking Unity3D's Scene Manager class which made test playing the levels much more comfortable. Furthermore the menu system allows to restart the current scene which also restarts the data capturing. One of the main advantages of using a game based setup, is that visual feedback can be given in real time. To exalt feedback a "strenghtometer", see Figure 20, was implemented as an UI-element displaying the current pinch strength. The meter can also be considered as an indicator stating the current tracking quality of the LMC. If the data displayed by the meter differs to much from the actual movement, skeletal tracking via the Leap API is unstable and repositioning the hand might remedy the situation. Due to lack of physical feedback, visual feedback had to be elevated even further and scripts were implement that change the colour of an object if it is gripped. In level two the holes also change colour if the pin is set properly in the respective hole. Hand models can be exchanged on the fly to the users preference by pressing the left or right arrow key, cycling through all available hand models to increase immersion. Grabbable objects are detected within a certain area surrounding the pinching hand. Multiple objects can be detected at same time. An adjustable parameter setting the maximal grab distance is then used to select the to be grabbed object. Vice-versa, a similar parameter is used to break the grip if the distance is greater then parameter's value. Invisible barriers have been included in the levels that prevent objects from getting to close to the LMC's interaction box edges. Furthermore a disconnection notice will be displayed as an overlay if the LMC is not connected. Like any other game, the virtual three dimensional world is mapped to a two dimensional display. This causes especially for users without video game experience, a lack of the depth perception. To retort this and

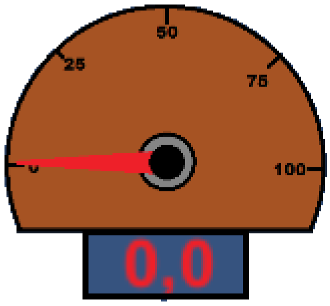

Figure 20: The pinch strength meter

therefore enhance the users immersion, soft shadows thrown by the hand models and interactive objects are enabled.

3.5 Game Logic

The main logic of the game is given in the game manager scripts that provide custom collider detection. Colliders are game objects that give feedback if they detect a specified collision. Grabbable object like the pins in level two use their default colliders and are labelled with custom tags allowing the collider logic to detect which collision is happening at the moment. Colour coding in level two therefore serves also as labelling to tag the pins. The planes located at the bottom of each hole, use a two dimensional collider that triggers the change of a Boolean value if a collision is detected, the object is no longer grabbed and the colours match. The game manager keeps track of the Boolean values and changes the scene if it is solved. Additionally to their own colliders, interactivity with objects is provided with the collider system specified for the hand. The hand consists of a set of box colliders, as can be seen in Figure 21, and the model that holds the texture is set upon (see Figure 22).

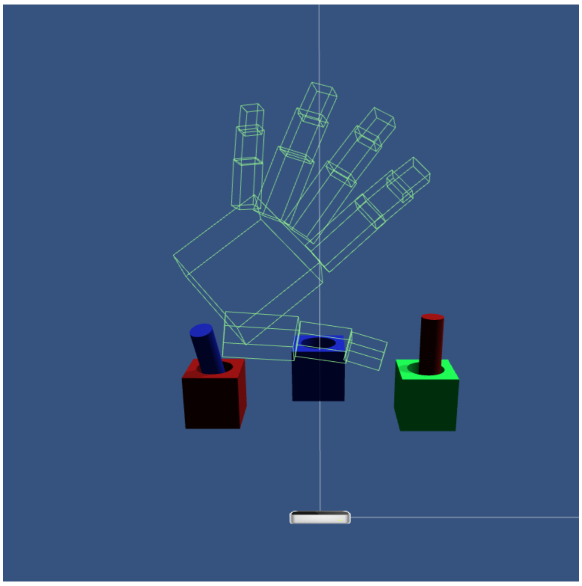

Figure 21: The collider set for the hand

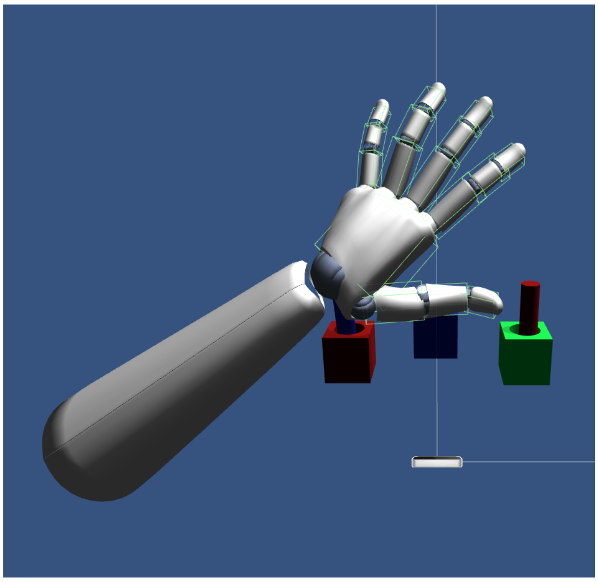

Figure 22: The model for the hand

3.6 Data Tracking

The Leap Motion software provides tracking data through a Web Socket server, initiated by the "leapd" process that runs as a daemon on Linux and OSX systems and as a service on Windows. This data can be accessed using the leapjs – a javascript client library for browsers and Nodejs. The tracking data will then be available as a .JSON file for each recorded frame, with the Leap running at up to 120 frames per second. The game on the other hand uses a custom made recorder, that stores positional tracking data directly as a comma separated value file. Using the recorder does not only reduce the amount of data, of which some is not relevant, but also ensures that the records represent interactions based on optical feedback given by the game. For this the recorder uses the update() function of Unity3D, that is called for each new frame, meaning that recording of data is reliant upon to the actual frame rate of the game, which differs depending on the used hardware for rendering the scene.

3.7 Related Work

Tarakci et al. (2019) have used a similar game setup to analyse the benefits of Leap Motion Controller based video game therapy as a training method for upper extremity rehabilitation. Their games consist of challenging the participant to either grab a ball and place it in the corresponding colour coded hole or to grip a bunny sticking out of a hole (see Figure 23 & 24)

Figure 23: Fizyosoft LeapBall

Figure 24: Fizyosoft CatchAPet

FlintRehab offers a variety of games which can be used as rehabilitation exercises involving custom made peripheral devices like the MusicGlove, see Figure 26, that has proven to be one of the more effective devices for home based rehabilitation training according to Zondervan et al. (2016), but misses the easy-to-use setup that is given when using a LMC, since it does not have to be worn. Vanbellingen et al. (2017) have analysed the usability of video game based therapy in the early rehabilitation phase for stroke patients and and rated the LMC based training systems usability as good to excellent. One of the reasons for the high usability is its possibility to make training comfortable as seen in Figure 25 where the patients (impaired) body can rest while training is focussed only on hand dexterity.

Figure 25: Leap training setup

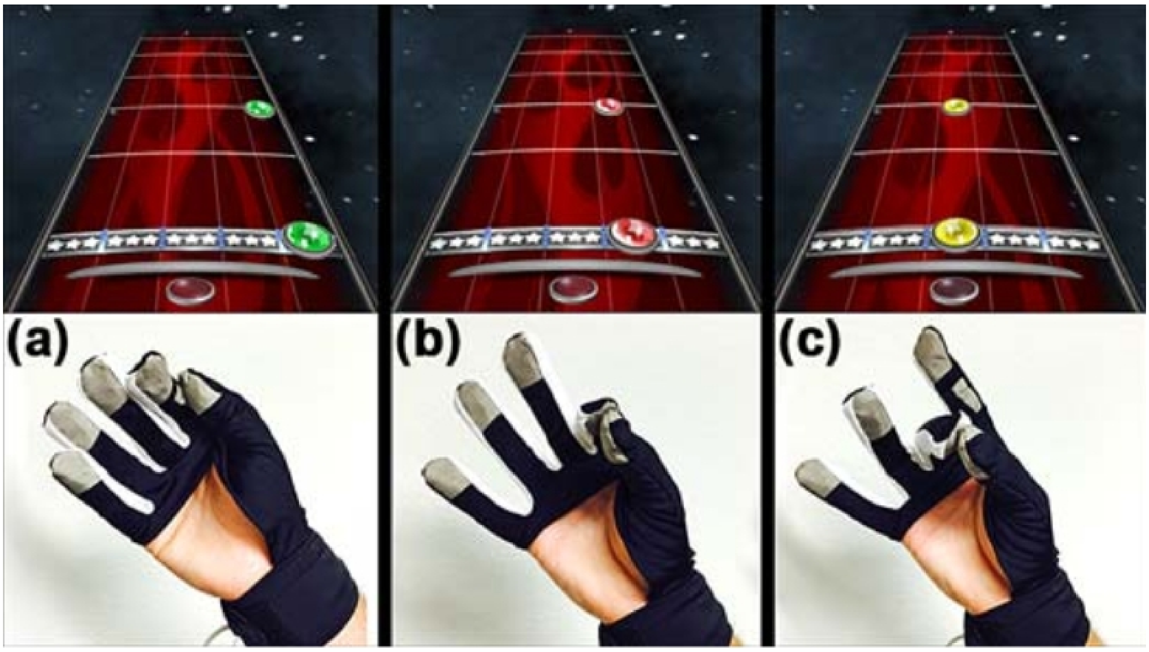

Figure 26: Flint Rehab MusicGlove

3.8 Limitations and Discussion

The game makes a very easy to use plug and play style motion capturing possible, while challenging the user with different but still repeatable tasks. The Leap Motion Core Asset Pack, although outdated, gives an easy to use framework that can be used and extended to the users preference. Using a high performance but user friendly game engine like Unity3D, allows to create games rapidly by re using and modifying existing scripts or prefabs. The game still is limited to the LMC's tracking quality and a game sided compensation is currently not possible. It can be argued that the hand collider set, as shown in Figure 22, could be improved to be more fitting by using capsule colliders instead or modifying the used colliders in a way to cover more of the hand model texture. Unlike the common NHPT, the test-retest coefficients appear to be rather low due to the enormous inter-trial time score differences for each untrained participant. Grasping a virtual object might differ significantly from grasping the somewhat same object in real life due to the constant need to not obstruct the LMC's view toward the gripping fingers, which eventually results in adapting to a specific way to grasp objects, depending on the participant. In any case, a "head-mount" even if not mounted to a VR-device, but rather to a head strap or a custom made scaffold which ensures that the LMC does not move while tracking, should be considered if changing the LMC's point of view promises a more precise tracking. Positioning the LMC other than on the desk facing upwards, or moving it while playing, is not possible for the game and should be avoided in general if a VR-device is not in use and therefore no movement data of the LMC itself can be captured. Using the LMC in a head-mount fashion (attached to a VR device) might be beneficial for increasing tracking persistence, depending on the use-case. Linux compatibility, might be discarded for future applications involving the LMC, since portability can be seen as a trade-off in terms of functionality, because the newer SDK versions are not available. Optimizing the setup, e.g. to be VR compatible would require more interactive features, which are to some extend, already given by the newer Leap "Orion" SDK that also promises vastly improved pinch and grab.

4 Summary

This thesis presented a game based approach to capture and assess hand kinematics using a Leap Motion Controller, compatible for both Windows and Linux operating systems. The game was developed using Unity3D, the 3D game engine of the Unity software development environment. Leap offers assets that can be used as a framework with access to the C# API that is required for creating scripts involving motion tracking. The game was used to analyse participants hand kinematics while playing its levels. All participants, were able to finish the game with their dominant hand as the main in-game controller.

Consistent capturing of tracking data, such as the position of hand joints, was possible and later used to assess participants hand kinematics and to examine a possible correlation between the unitless build-in pinch strength parameter of the Leap skeletal tracking and a real world measurement of forces exchanged on a physical object while performing a pinch grip.

Appendix A:

Table 1: Example window view for recorded data (**Participant ID: 13_1**)

Timestamp	PinchStren	isright	thumb-tipX	thumb-tipY	thumb-tipZ	ring-j0Z	pinky-tipX	pinky-tipY	pinky-tipZ	pinky-j3X	pinky-j3Y	pinky-j1Z	...
...													
10.12795	0	False	0.9126276	3.279532	-2.184205	-2.886119	-1.651821	3.981468	-0.3339922	-1.574773	4.051804	-1.709366	
10.22823	0	False	0.8997119	3.09173	-2.140304	-2.842153	-1.673365	3.731864	-0.3009775	-1.595104	3.807878	-1.671014	
10.32789	0	False	0.8454481	2.98324	-2.085025	-2.786339	-1.746273	3.596265	-0.2549357	-1.664562	3.674483	-1.619056	
10.42934	0	False	0.7690656	2.907534	-2.009943	-2.713381	-1.827149	3.532988	-0.1906479	-1.741383	3.612005	-1.549287	
10.52819	0	False	0.7279457	2.863652	-1.943478	-2.655123	-1.88195	3.485388	-0.1395679	-1.792887	3.565363	-1.492955	
10.62791	0	False	0.6853481	2.764217	-1.860303	-2.575098	-1.923764	3.382695	-0.06563291	-1.833626	3.465155	-1.41554	
10.72786	0	False	0.6450095	2.617322	-1.820028	-2.529891	-1.952077	3.209413	-0.03089405	-1.862337	3.299271	-1.374517	
10.82977	0	False	0.5964576	2.449581	-1.798761	-2.504253	-1.986744	3.007297	-0.02468883	-1.895447	3.10478	-1.357688	
10.92797	0	False	0.5241653	2.344798	-1.764843	-2.505544	-1.979603	2.930838	-0.02189577	-1.890892	3.029489	-1.356444	
11.02938	0.3053248	False	0.3851711	2.257566	-1.660978	-2.495555	-1.970106	2.911635	-0.009240962	-1.882192	3.009522	-1.345514	
11.12781	0.4424392	False	0.3597522	2.2830	-1.618344	-2.489072	-1.950073	2.941931	0.005549106	-1.8633	3.03453	-1.33749	
11.22718	0.5515764	False	0.3394201	2.37174	-1.565674	-2.47511	-1.935919	3.039657	0.02063352	-1.847759	3.127705	-1.325128	
11.32782	0.5923437	False	0.3426719	2.474034	-1.570093	-2.493555	-1.929775	3.159369	0.005551863	-1.84076	3.243065	-1.34334	
11.42805	0.6168262	False	0.3336847	2.614841	-1.588529	-2.516515	-1.926816	3.318862	-0.01481396	-1.838913	3.401201	-1.366858	
11.52799	0.6681135	False	0.320633	2.757293	-1.59826	-2.536203	-1.918016	3.499919	-0.03146124	-1.830182	3.579858	-1.386295	
11.62789	0.6873646	False	0.3397099	2.865632	-1.623489	-2.559438	-1.886826	3.612109	-0.049659	-1.802855	3.69241	-1.409322	
11.72731	0.6977144	False	0.3570398	2.909246	-1.624774	-2.572209	-1.864582	3.665305	-0.05666143	-1.782465	3.744243	-1.419527	
11.82918	0.7150505	False	0.3774715	3.025014	-1.608305	-2.570404	-1.82445	3.814013	-0.04696587	-1.743792	3.889854	-1.413825	
11.92717	0.7283599	False	0.3891532	3.13806	-1.602036	-2.570004	-1.794657	3.958096	-0.03999941	-1.7155	4.031769	-1.410407	
12.02684	0.7421656	False	0.3996622	3.248696	-1.563892	-2.545533	-1.779366	4.075948	-0.01101641	-1.702034	4.148316	-1.383852	
12.12834	0.7745712	False	0.4248177	3.375591	-1.5222	-2.509636	-1.742328	4.218879	0.03017075	-1.667324	4.290311	-1.345505	
12.22267	0.7809725	False	0.4416339	3.451594	-1.49809	-2.489337	-1.721853	4.306473	0.05092666	-1.647297	4.377183	-1.325383	
12.32731	0.7879931	False	0.4575813	3.632264	-1.420504	-2.419549	-1.682903	4.528758	0.1291632	-1.61049	4.595979	-1.251191	
12.42806	0.787258	False	0.4471995	3.738499	-1.355039	-2.363022	-1.686146	4.627405	0.1898838	-1.616867	4.695319	-1.192876	
12.53057	0.7887563	False	0.4327709	3.762127	-1.271855	-2.300054	-1.692315	4.649531	0.2572147	-1.625618	4.717379	-1.127669	
12.63371	0.7663898	False	0.4067977	3.750301	-1.183577	-2.22001	-1.710431	4.627999	0.3428893	-1.646077	4.696244	-1.044499	
12.73315	0.7509242	False	0.3669471	3.675832	-1.084716	-2.131995	-1.74443	4.531983	0.431785	-1.680577	4.605411	-0.9545158	
12.82698	0.7494385	False	0.3447914	3.597437	-1.004348	-2.060115	-1.762536	4.405469	0.5053356	-1.700775	4.4836	-0.8807937	
12.92897	0.745054	False	0.3454309	3.526918	-0.9263848	-1.98007	-1.775895	4.292682	0.5792685	-1.712871	4.374693	-0.8030323	
13.02099	0.7362472	False	0.3444942	3.468037	-0.8810277	-1.928552	-1.789825	4.213631	0.6279114	-1.725758	4.29723	-0.7522147	
13.12738	0.726226	False	0.3353468	3.370048	-0.8458269	-1.875481	-1.799894	4.087299	0.6754	-1.735326	4.175613	-0.7006056	
...													

Appendix B:

Image Resources (as of 20.12.2019)

Figure 1 taken from:

www.blog.leapmotion.com/hardware-to-software-how-does-the-leap-motion-controller-work

Figure 2 taken from:

https://medium.com/@puneetrawat9995/hand-tracking-in-oculus-quest-vs-leap-motion-and-the-future-of-leap-motion-in-vr-337ffe6b60e2

Figure 3 taken from:

https://developer.leapmotion.com/documentation/v4/vrar.html

Figure 4 taken from:

http://www.nle.nottingham.ac.uk/websites/rheumatology/chapter4.html

Figure 5 taken from: Martin-Brevet et al., 2017

https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0178185

Figure 6 taken from:

http://blog.leapmotion.com/skeletal-tracking-101-getting-started-with-the-bone-api-and-rigged-hands/

Figure 7 taken from:

http://blog.leapmotion.com/understanding-latency-part-2/

Figure 8 taken from:

www.developer.leapmotion.com/setup/desktop

Figure 14 taken from:

https://developer-archive.leapmotion.com/documentation/v2/csharp/devguide/Leap_Coordinate_Mapping.html

Figure 19 taken from:

https://forum.unity.com/threads/interesting-facts-unity-and-maya-uses-different-xyz-vectors-with-the-real-math-vectors.393538/

Figure 23 and 24 taken from:

Tarakci et al., *Leap Motion Controller–based training for upper extremity rehabilitation in children and adolescents with physical disabilities: A randomized controlled trial*, 2019

Figure 25 taken from:

Vanbellingen et al.

Usability of videogame-based dexterity training in the early rehabilitation phase of stroke patients: a pilot study, 2017

Figure 26 taken from:

Zondervan et al., *Home-based hand rehabilitation after chronic stroke: Randomized, controlled single-blind trial comparing the MusicGlove with a conventional exercise program*, 2016

APPENDIX C : List of Abbreviations

LMC – Leap Motion Controller
VR – Virtual reality
JSON – Javascript object notation
SDK – software development kit
e.g. - for example
FPS – First Person Shooter
prefab – prefabricated game object
API – application programming interface
UI – User interface
NHPT – Nine Hole Peg Test

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Official Unity Website: www.unity.com
V2 tracking: www.developer.leapmotion.com/setup/desktop
Unity Scripting API Documentation:
www.docs.unity3d.com/ScriptReference/Time-timeSinceLevelLoad.html
Leap C# API Documentation:
www.developer-archive.leapmotion.com/documentation/v2/csharp/devguide/Leap_Overview.html?proglang=csharp
Unity Assets Manual: https://docs.unity3d.com/Manual/AssetWorkflow.html
GitHub for Leap Motion Core Asset pack for version 2.3.1:
www.github.com/leapmotion/LeapMotionCoreAssets/releases?after=prerelease-v2.4.0
ProBuilder Website:
https://unity3d.com/de/unity/features/worldbuilding/probuilder
TextMeshPro Assets:
www.assetstore.unity.com/packages/essentials/beta-projects/textmesh-pro-84126
Unity Scene Manager API Documentation:
www.docs.unity3d.com/ScriptReference/SceneManagement.SceneManager.html
GitHub for LeapJS: www.github.com/leapmotion/leapjs
Official Leap Project Orion Website: www.developer.leapmotion.com/orion
Leap API Reference PinchStrenght:
https://developer-archive.leapmotion.com/documentation/v2/csharp/api/Leap.Hand.html?highlight=pinchstrength#Hand.pinchStrength
LeapC API Documentation (documentation for v4):
https://developer.leapmotion.com/documentation/v4/
Official Flint Rehab Website:
www.flintrehab.com
Unity Scripting API update() function:
www.docs.unity3d.com/ScriptReference/MonoBehaviour.Update.html
The Game at GitHub:
https://github.com/dombmann/Bachelor_Game