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Surgical Animations in Anatomical Education

Development and feasability study of a case based augmented reality application

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SURGICAL ANIMATIONS IN ANATOMICAL EDUCATION

Development and feasibility study of a case based augmented reality application

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Laura Ligthart,
Leiden, February 2022

Abstract

Augmented reality (AR) promises to be a valuable tool for anatomical education since any given anatomical site can be studied dynamically in three dimensions (3D). Yet, it has not been used with case-based learning in medical education despite the latter's demonstrated benefits. This research, thus, investigates the potential benefit of 3D holographic animated surgeries on functional anatomical knowledge acquisition. We developed four educational AR applications comparing two cases with and without the presence of a surgical animation. Based on this, a randomized crossover trial was conducted among second year medicine students. All subjects ($n = 10$) underwent a spatial visualization assessment, followed by a learning session and an anatomical knowledge test for both patient cases. The presence of a surgical animation did not lead to a significant difference in anatomical test scores. In addition, no correlation ($\tau = -0.092$, $p = 0.78$) was detected between the effect of surgical animations and spatial visualization abilities. However, these results are based on non-parametric statistics, as normality could not be assumed. Further research with samples representative for the population, conducting both qualitative and quantitative analysis using verified outcome measures and parametric statistics is required to draw accurate conclusions.

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1

Introduction

Gross anatomical knowledge is essential for understanding physiological and pathophysiological mechanisms of the human body, making it a crucial part in medical education. Traditionally, it is taught using various methods (Estai and Bunt, 2016; Youssef, 2021), whereby cadaveric dissection has been the preferred approach for centuries (Magee, 2001). Although this method is considered useful and effective (Anyanwu and Ugochukwu, 2010; Biasutto et al., 2006), there are some limitations, namely the financial expenses and time cost inherent to this method (Aziz et al., 2002). Moreover, for students having their first encounter with cadavers (e.g. dissection, prosection or plastination), it may be hard to distinguish and identify different structures due to the lack in colour diversity (Ejaz et al., 2014). Anatomical atlases assist to overcome these limitations. However, their two dimensional (2D) nature requires the student to mentally converge the images into a three dimensional (3D) model to comprehend the full scope of the anatomy (Garg et al., 2001; Tavanti and Lind, 2001). Additionally, direct interaction is showing clear advantages for spatial and anatomical learning as compared to passive viewing (Garg et al., 2001; Jang et al., 2017).

Various studies have explored the possibility to implement virtual reality (VR) and augmented reality (AR) into medical education using head mounted displays (HMDs) (Barteit et al., 2021). With these techniques any given anatomical site can be studied dynamically and stereoscopically in full 3D[1]. Compared to VR, AR shows a reduced occurrence of motion sickness for the user (Lawson and Stanney, 2021) and allows for normal visual interactions between individuals (e.g. teacher and student). Previous research stated that AR can be a promising tool for anatomical education (Barteit et al.,

[1] As opposed to 3D models projected onto a 2D screen.

2021; Bogomolova et al., 2020; Chytas et al., 2020; Moro et al., 2017, 2021; Romand et al., 2020; Yong et al., 2018), resulting in a better learning performance (Bogomolova et al., 2020; Chytas et al., 2020; Moro et al., 2017; Yong et al., 2018), increased immersion and engagement (Moro et al., 2017) with greater enthusiasm and more enjoyment (Barteit et al., 2021; Bogomolova et al., 2020; Yong et al., 2018). However, these studies are focused on physiological anatomy. Case based learning, which has shown its impact on medical education (McLean, 2016; Peixoto et al., 2017; Wood, 2003) closer resemble the situations health professionals are confronted with in their daily practice.

A surgery can drastically change the pathophysiological anatomy, which may result in an unusual postoperative situation. Implementing such clinical cases in anatomical education could be useful for students to develop clinical reasoning and diagnostic performance. The use of 3D animations lead to a better understanding of difficult surgical topics as compared to traditional surgical videos (Prinz et al., 2005). Based on this and the benefits of interactive learning, the aim of this study is to evaluate the effect of 3D holographic animated surgical procedures on functional anatomical knowledge acquisition. Secondary objectives are to evaluate possible modifying effects (i.e. test difficulty dissimilarities or a learning curve) on the outcome and to correlate the effect of surgical animations with spatial visualization abilities.

2

Design and Methods

A randomized crossover trial was conducted at the Leiden University Medical Center (LUMC) in October 2021. The study protocol was approved by the research committee of the department of Orthopedics. The Medical Research Ethics Committee (Dutch abbreviation: METC) confirmed that the Medical Research Involving Human Subjects Act (Dutch abbreviation: WMO) does not apply for this study (registration number N21.125).

2.1 | Participants

Second year medical students at the Leiden University Medical Center were recruited. The majority of this population is between 18 and 21 years of age and 60-75% is female. If students followed a course where the anatomy of the limbs has been discussed and studied profoundly, they were excluded from the study. This involved prior education, as well as an extra-curricular course or participation in previous research on this topic. Participation was on a voluntary basis meaning the enrolled students did get neither European Credit Transfer System (ECTS) points nor financial compensation. Participation did not intervene with the curriculum and the test results did not have any influence on the student's academic grades. All students were informed through an information letter and video, and signed an informed consent form. Afterwards, base characteristics were registered, consisting of age and gender.

2.2 | Randomization and Blinding

Randomisation was carried out by drawing folded papers with a research number (a random 5 digit number). After randomisation, the student was only referred to by the research number in documents. This number could not be traced back to the student. The students and the researcher were not blinded at the time of the experiment, but the corrector grading the anatomical tests was.

2.3 | Application Development

The AR application *DynamicAnatomy* developed by Bogomolova et al. (2021) (Department of Anatomy, LUMC, Leiden, The Netherlands), has been further developed to fulfil the objectives of this research. The application has been used as an investigational product before (Bogomolova et al., 2020) and is developed for the Microsoft Hololens (version 1, Microsoft, Redmond, Washington, USA).

The existing application contained a dynamic and interactive stereoscopic 3D model of the lower extremity, reaching up until the knee (Figure 2.1).

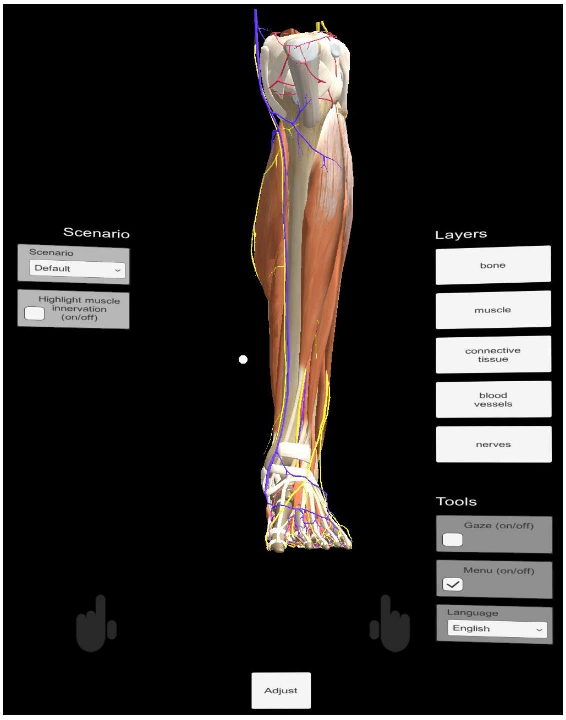


Figure 2.1: The foundation of the original *DynamicAnatomy* Augmented Reality application used for further development.

This holographic AR model, which is adjustable in size, can be projected into the physical space of the user at any fixed place. Its 360° view allows the user to walk around and perceive the model from all sides. Hereby, the menu is always facing the user. The user has the possibility to show or hide anatomical structures, either as a group (i.e. type of tissue) or individually. Four basic movements of the tibiotalar joint (dorsiflexion and plantarflexion) and the talocalcaneal joint (inversion and eversion) were incorporated through buttons or voice commands.

For the purpose of this research, the following features were added to this application: 1) preoperative and postoperative scenarios of complex surgical case, 2) a surgical animation, 3) interactive joint movements using a gyroscope and 4) muscle innervation of the large nerves. Additionally, an identical application of the upper extremity was created, incorporated with a pronation and supination movement. The implemented cases consist of a tibialis posterior tendon transfer for the lower extremity and a pronation osteotomy for the upper extremity.

The surgical animations were developed through editing the upper and lower extremity models in Blender (Blender Foundation, Amsterdam, The Netherlands). The development was fulfilled in collaboration with two orthopaedic surgeons in order to closely represent a real surgery. The animation was then imported in Unity 3D (Unity Technologies, San Francisco, California, USA), where interactive elements were added to the application (Figure 2.2).

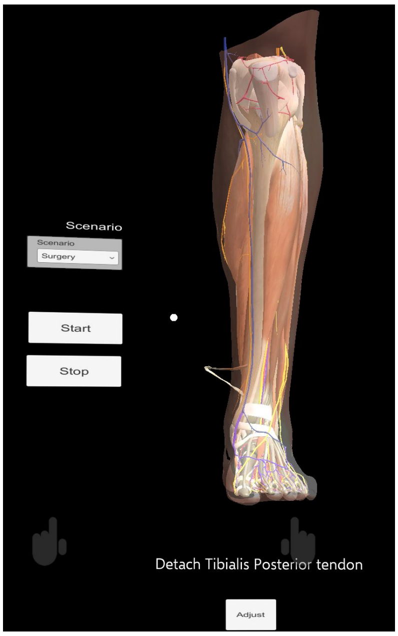


Figure 2.2: A fragment of the tibialis posterior transfer surgery.

Interactive joint movements are facilitated through an Android application. This application is developed such that an Android smartphone (client) can pair to the HoloLens (host) over Wireless Fidelity (Wi-Fi) connection (Figure 2.3). After pairing, the local coordinates of the smartphone's gyroscope are shared in real-time with the HoloLens. In this manner, the rotation of the joints follows the rotation of the paired gyroscope. The range of motion of each interactive joint is programmed to represent the specific range of motion for each of the given scenarios (e.g. default, preoperative or postoperative).

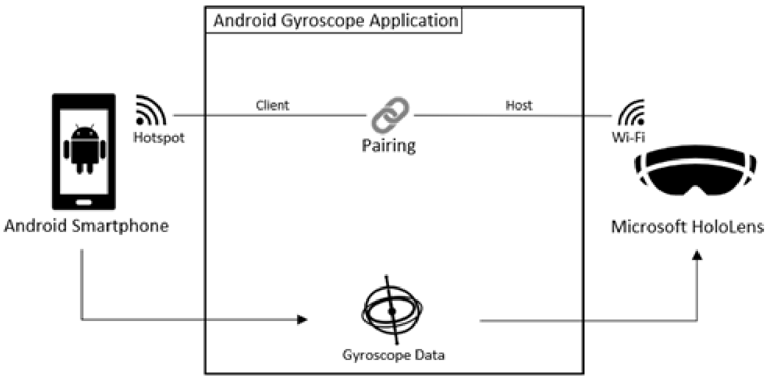


Figure 2.3: Schematic diagram of the Android application functionality.

Lastly, innervation of the large nerves was implemented by illuminating the muscles that it innervates (Figure 2.4). The development is described more thoroughly the appendices of this research (Appendix A).

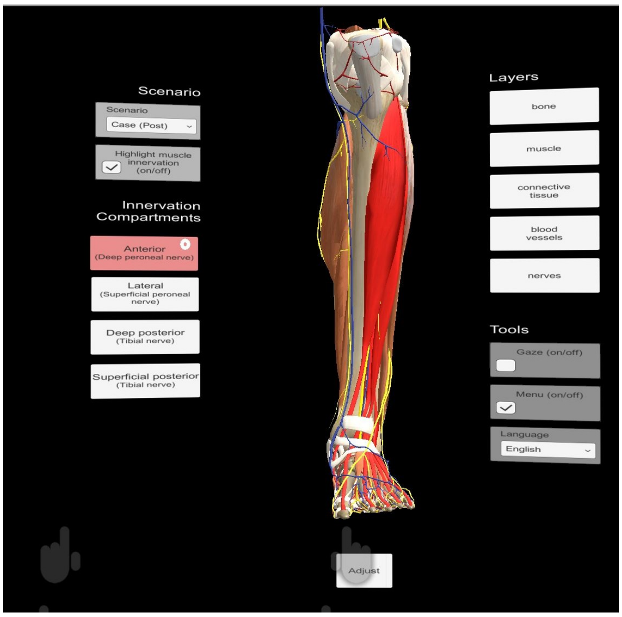


Figure 2.4: The HoloLens application, showing an illuminated Anterior compartment of the leg, which is innervated by the deep peroneal nerve.

In total, four AR applications were built. A overview of their implemented cases and scenarios is given in Table 2.1. Two applications contained the lower extremity model (one with and one without a surgical animation) and in the same manner two applications contained a model of the upper extremity. Additionally, one Android application was built which can be installed on any Android smartphone with a gyroscope and can be paired with the Microsoft HoloLens through a Wi-Fi connection.

Table 2.1: Overview of the developed HoloLens applications and their implemented scenarios.

	Lower extremity *Tibialis posterior tendon transfer*	**Upper extremity** *Pronation osteotomy*
Intervention case	Default Preoperative Surgical Postoperative	Default Preoperative Surgical Postoperative
Control case	Default Preoperative Postoperative	Default Preoperative Postoperative

2.4 | Experiment Design

The experiment procedure is illustrated in Figure 2.5. The students were divided into two groups. One group studied their intervention case first, the other their control case. This sequence, along with the categorization of the intervention and control case was decided through randomisation.

The student could study the following models for their control case: 1) default, 2) preoperative model and 3) postoperative model. For their intervention case, the students could study the same models, but had access to an animation of the surgery as well.

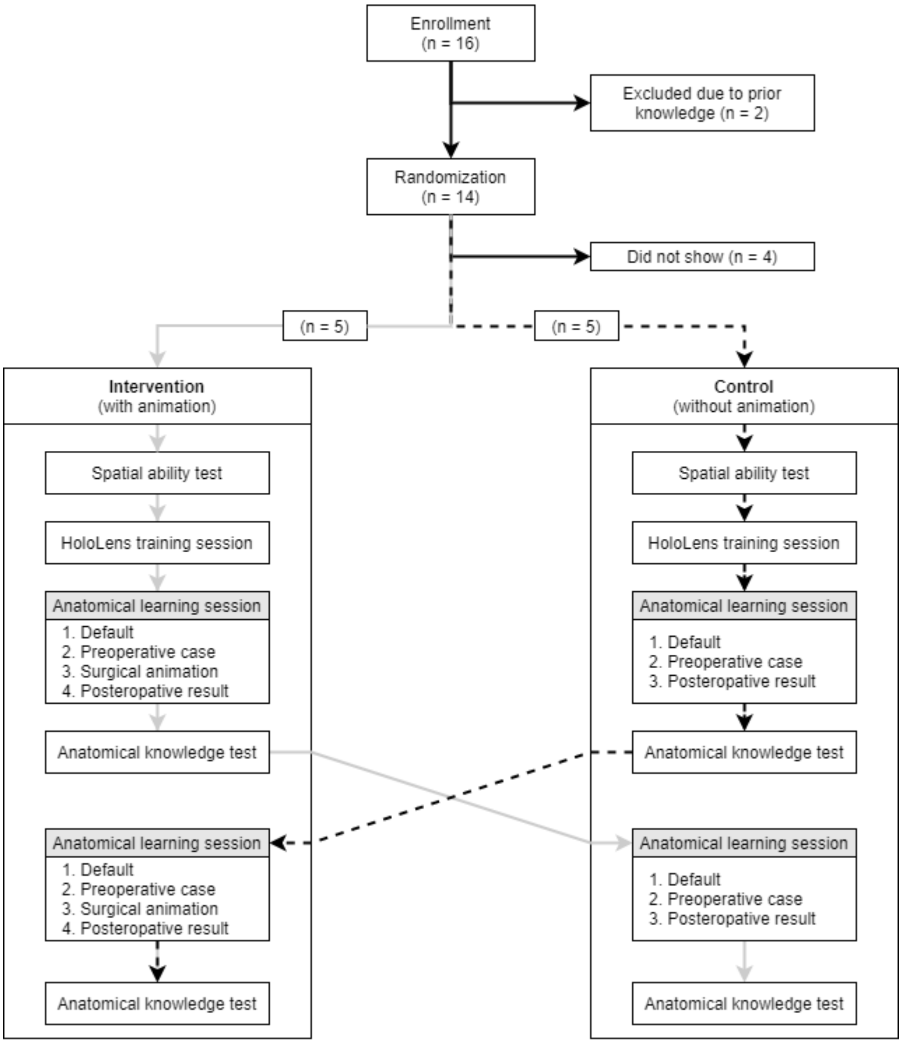


Figure 2.5: Flowchart of study design, n = number of participants.

The participants first performed a visual-spatial ability assessment, followed by a training session called *Learn Gestures* (Microsoft, Redmond, Washington, USA) to become familiar with the gestures used to control the Microsoft HoloLens. Then, they started with the anatomical learning session for their first case, followed by a respective anatomical knowledge test. After crossover, the participants studied their second case using the corresponding application. Finally, another anatomical knowledge test was conducted.

2.5 | Spatial Visualization Assessment

The student's spatial visualization was assessed using the mental rotation test (MRT) from Shepard and Metzler (1971), validated by Vandenberg and Kuse (1978) and redrawn by Peters et al. (1995). After reading the instructions, the students had ten minutes to complete the 24-item test.

2.6 | Learning Objectives and Instructions

Each participant received the same two handouts, stating learning objectives and instructions (Appendix B.1 and B.2) for the two cases. Using these handouts, the students underwent a 15 minute learning session, during which they were independent in their approach of achieving the learning goals. The participants were not allowed to keep the handouts during the anatomical knowledge assessment.

2.7 | Anatomy Knowledge Assessment

Anatomical knowledge was assessed trough two anatomical knowledge tests, one for each case (Appendix C.1 and C.2). Both tests contained 6 questions, consisting of extended matching along with open questions, and had a maximum score of 21 points. The questions in both tests concern functional anatomy prior to and after surgery. Both the questions and their answers were validated in collaboration with two orthopedic surgeons with experience in education. The students had ten minutes to complete the each test, which was scored with the percentage of correct answers.

2.8 | Statistical Analysis

The student's baseline characteristics were summarized using descriptive statistics. The distribution of the scores from the MRT test and both anatomical tests were assessed and compared to a normal distribution using the Shapiro-Wilk test along with Normal quantile-quantile (Q-Q) Plots. The two anatomical tests were compared for similarity, using box-plots with a five-number summary. A learning curve and the effect of the surgical animation were assessed using the Wilcoxon Signed-Rank test, using a two-tailed test and a significance level of $\alpha = 0.05$. The MRT score was compared with the difference in individual anatomical test scores for which the Kendall's τ correlation was calculated.

3

Results

3.1 | Participants

A total of 16 participants were enrolled in this study. However, two participants were excluded due to prior knowledge and an additional four - which were already randomised - did not show or resigned before any data was gathered. Subsequently, 10 participants completed the study (Figure 2.5). Five of these participants were randomised with the intervention before crossover and control afterwards, and vice versa for the remaining five students. The participants aged between 18 and 22 years and had a mean age of 19.8 years. Six of them were female, resulting in a male-female ratio of 2:3.

3.2 | Normality

The Shapiro Wilk test showed that no normal distribution can be assumed for the MRT ($p = 0.2638$), as well as both the lower extremity ($p = 0.3278$) and upper extremity ($p = 0.6055$) anatomical knowledge tests. Likewise, the Normal Q-Q Plots (displayed in appendix E) show no linear relationship in the data points between the theoretical quantiles and sample quantiles.

3.3 | Anatomical Test Similarities

The scores of both anatomical tests are visualised with boxplots in Figure 3.1. The lower and upper quartile are with 23.81% and 42.86% respectively exactly the same for both tests. The median of the lower extremity test is with a score of 35.7% slightly higher than the upper extremity test with a median of 30.95%. Additionally, the upper extremity test had a lower minimum and a higher maximum test result (14.29% and 61.90% respectively) compared to the anatomical test of the lower extremity (19.04% and 47.62%).

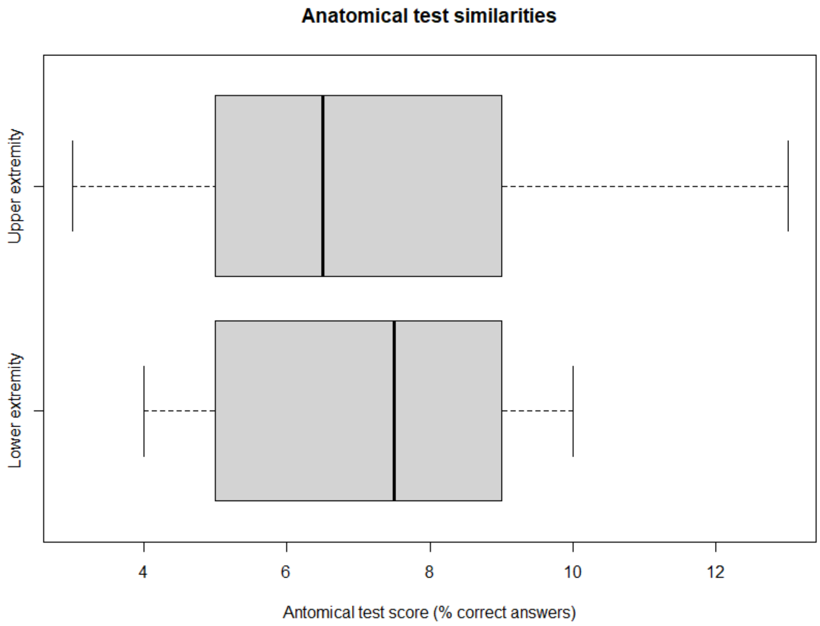


Figure 3.1: Two box plots showing test score of the two anatomical knowledge tests, with on the horizontal axis the test score shown in the percentage of correct answers.

3.4 | Learning Curve

The first anatomical test completed by each student is compared with the outcome of their second anatomical test to assess for a potential learning curve. A scatter plot with the anatomical test scores for both cases is shown in Figure 3.2.

Three students received a higher score for their first test and five students for their second test. The remaining two students scored the same on both tests. For four out of the five students with a better second test result, the second test corresponds with the intervention case. Similarly, for two out of the three students with a better first test result, that test corresponds with the intervention case. The W-value calculated with the Wilcoxon Signed-Rank Test is 17, while the critical value is 3 for a two-tailed test with a significance level of $\alpha = 0.05$ at $n = 8$.

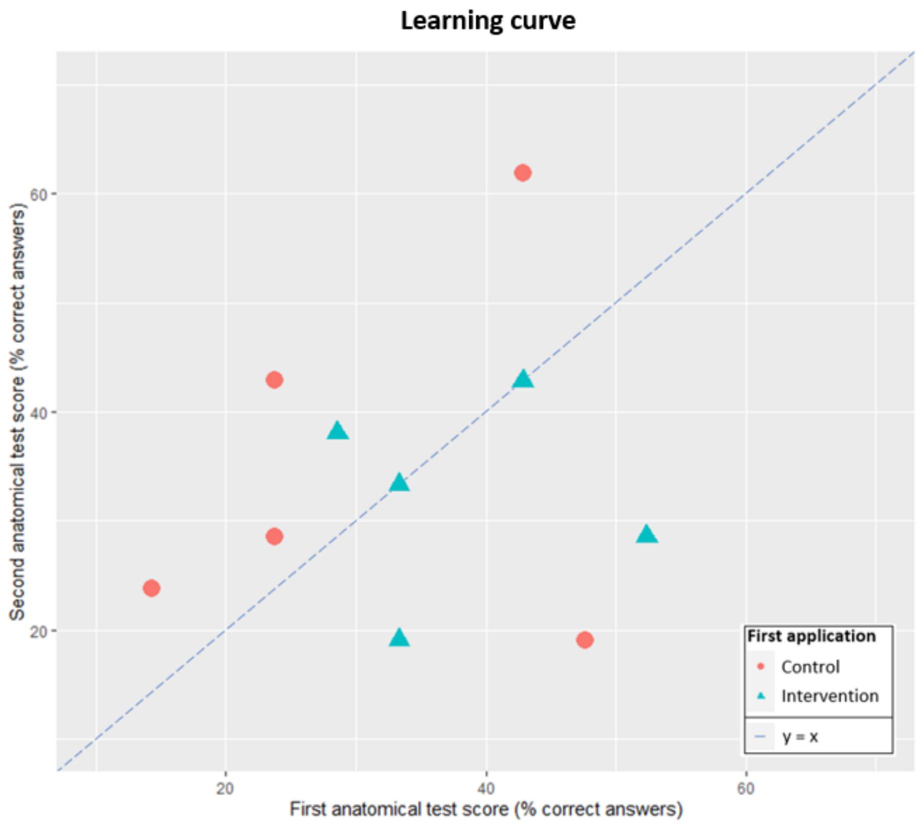


Figure 3.2: Scatter plot showing the scores for the first and second anatomical knowledge test, with the test scores in percentage of correct answers. Red circles: participants that initiated as control; green triangles: participants that begun with the intervention. The blue dashed line ($y = x$) corresponds to equal test results for both tests.

3.5 | Surgical Animation Effect

To assess the effect of a surgical animation on the anatomical knowledge of the students, the anatomical tests of their intervention and control case are compared. In figure 2.2, the test scores of each student are plotted. On the horizontal axis, the anatomical test results for the control cases are displayed and on the vertical axis those of the intervention cases. Additionally, the blue dashed line $x = y$ indicates an equal test score for intervention and control. As seen in Figure 3.3, six students have a higher score for the anatomical knowledge test of their intervention case, two students have the same result for both tests and two students a lower score for the test belonging to their intervention case. The Wilcoxon Signed-Rank Test results in a W-value of 11 between control and intervention, with a critical value of 3.

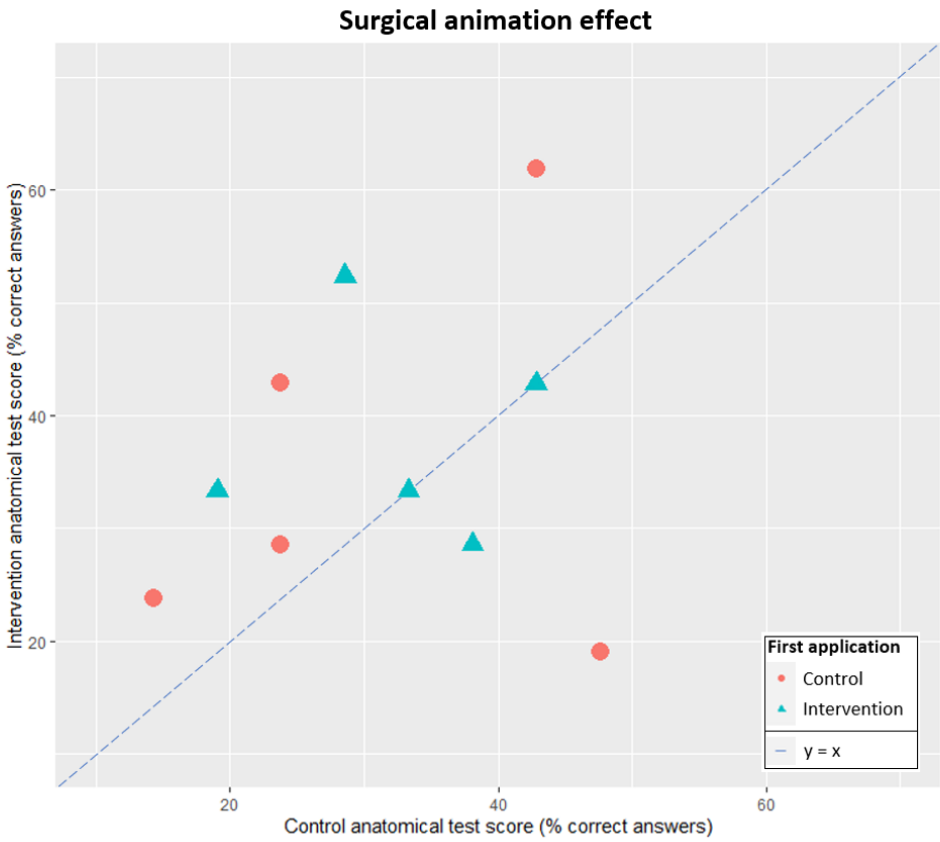


Figure 3.3: Scatter plot showing the results for the intervention and control anatomical knowledge tests. The test scores are given in % of correct answers. Red circles: participants that first studied their control case. Green triangles: participants that studied their intervention case first. The blue dashed line ($y = x$) corresponds with equal test results for both anatomical tests.

3.6 | Spatial Visualization Abilities

The median MRT score is 16.5, with a lower quartile of 15 and a upper quartile of 21. The minimal score is 2 and the maximal score of 24 is equal to the maximal score of the test. In Figure 3.4, the difference in score between the two anatomical tests is compared with the MRT score. The correlation according to Kendall's τ coefficient is -0.092 ($p = 0.78$).

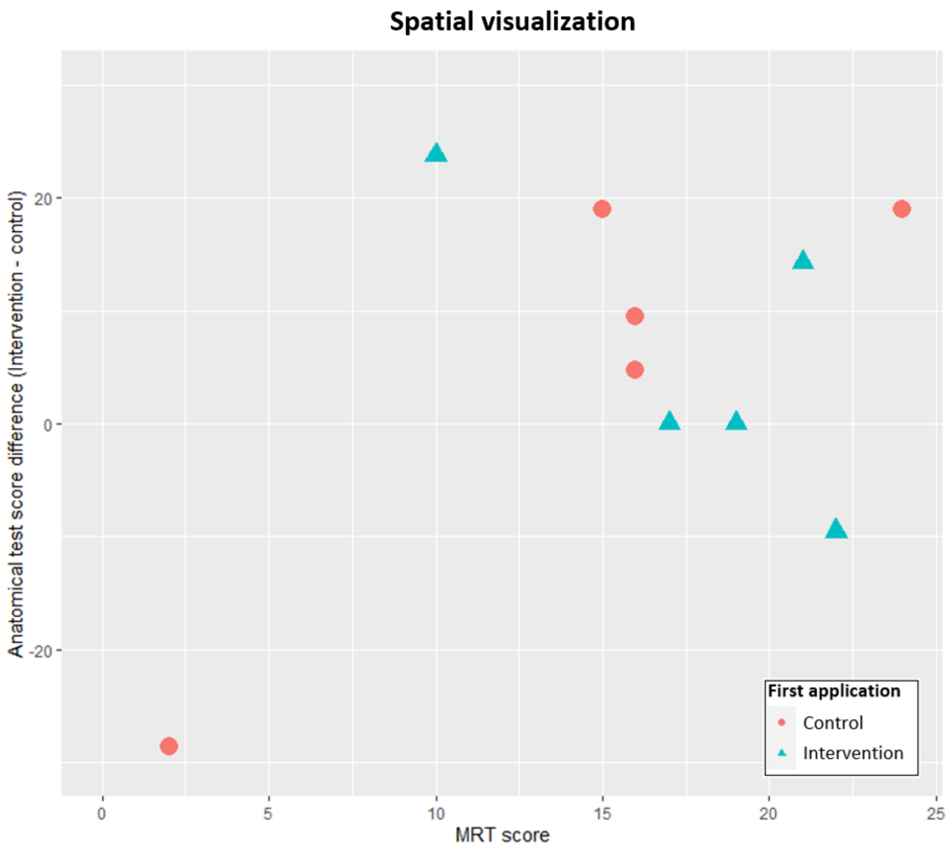


Figure 3.4: Scatter plot showing the MRT score and the difference (in percentage of correct answers) between the two anatomical test scores. Red circles: participants that first studied their control case. Green triangles: participants that studied their intervention case first.

4

Discussion

In the frame of this research, first four applications for the Microsoft HoloLens were developed. Their aim is to evaluate the effect of 3D holographic animated surgical procedures on the functional anatomical knowledge acquisition of medical students. To quantify their impact, the second and third phase of the research saw the design and conduction of experiments with medical students.
The development process of the applications is discussed in appendix A. Below, the experiment design and outcome are discussed.

Experiment Design
A randomized crossover trial was designed to reduce confounding covariates. Test similarity was measured by comparing overall scores of the lower extremity anatomical test with those of the upper extremity. Apart from this, all effects were measured with outcomes of individual subjects. Modifying effects due to a possible learning curve or test dissimilarities are mitigated due to randomizing the test sequence and the categorization of the intervention and control case. The intervention effect is defined as the difference between the intervention and control anatomical test scores. The presence of a correlation between this intervention effect and spatial abilities was assessed. These results are discussed below.

Experiment Outcomes
The majority of the participants obtained a better result for the anatomical test of their intervention case as compared to their control case. However, this difference is not statistically significant. While the absence of a learning curve and test dissimilarities exclude these factors as modifying effects on the outcome, possible explanations are stated in the limitations section.

Literature shows that a majority of the research regarding the use of AR in medical education is qualitative and in favor of AR (Uruthiralingam and Rea, 2020). However, quantitative meta-analysis suggested that AR has no significant beneficial effects on learning anatomy compared with other teaching techniques (Bölek et al., 2021). Our research additionally suggests that the presence or absence of an animated surgery by means of AR has no significant effect on functional anatomical knowledge acquisition. It is imperative to explore the discrepancy between these qualitative and quantitative results.

We found no significant correlation between the intervention effect and the MRT score. However, with a median MRT score of 16.5, the participants scored comparatively high, as compared to undergraduate students in previous research, while other factors were similar. In the study of Caissie et al. (2009), a mean MRT score of 11.45 (SD = 6.12) was obtained by 624 undergraduate students (407 women, 217 men) with a mean age of 21. Other research shows that medical students have a statistically higher spatial ability, than educational studies students. This is beneficial for learning anatomy (Vorstenbosch et al., 2013). Moreover, spatial abilities can be trained by learning anatomy (Guillot et al., 2007; Langlois et al., 2020; Vorstenbosch et al., 2013). As such, the high spatial ability of the second year medical students included in this study may be a result of training. However, a bias due to voluntary participation cannot be excluded.

4.1 | Limitations

The generalizability of our results is impacted by the small sample size which is not representative for a normal distributed population. Further, voluntary participation may result in differences between the volunteers and the target population, resulting in a volunteer bias. That is, volunteers are more likely to outperform others in medical education research, and women and ethnic minorities have a lower representation (Callahan et al., 2007).

Nevertheless, the anatomical test was performed with unsatisfactory quality. In order to avoid poor data distribution only correct answers were scored. This was not mentioned on the anatomical tests and therefore did not impact the subject.

Logging the buttons the students clicked during the anatomical learning session could have given more insights in the reason behind these unsatisfactory test results and differences in results in general. As logging button clicks was not updated in the applications, it remains unknown which of the available scenario's the participants actually studied. The participants reported the anatomical tests to be hard, but no standardized survey was given to accurately evaluate student opinion. Their main criticism was the field of view size of the HoloLens, which they believed to be too small for adequate use in medical education. Further, participants evaluated the HoloLens not comfortable enough to use for longer periods of time: one student reported a headache, and another student reported fitting difficulties. Although cybersickness is less of a problem in AR than in VR, it can still cause adverse health effects like dizziness, general discomfort and headaches (Moro et al., 2021). If these factors would be improved, the participants would see a place for using AR in medical education.

4.2 | Recommendations for Future Research

To better understand the strengths and shortcomings of AR for medical education, future research should focus on the discrepancy between qualitative and quantitative research this field. We recommended to conduct a randomized crossover trial using samples representative for the population, while focusing on both qualitative and quantitative analysis using verified outcome measures. Additionally, logging the usage of the application by a participant could give new insights and possibly support their qualitative and quantitative results.

Apart from this, participant discomfort may be reduced by using the Microsoft HoloLens 2, which has a bigger field of view and is more evenly distributed in weight (Microsoft, 2021b).

5

Conclusions

We developed four applications for the Microsoft HoloLens aiming to improve anatomical education. Next to a default scenario, a preoperative and a postoperative scenario of two complex surgical cases were implemented. The range of motion of the examined joints in each of these scenarios can be studied interactively by using a paired Android smartphone. On top of that, surgical animations were implemented for the intervention case. These developments can be used as a foundation for further research.

Experiments were designed based on these applications examining the effect of surgical animations with AR. The conducted experiments did not lead to a significant difference on the functional knowledge acquisition of medical students. Additionally, no statically significant correlation was found between the intervention effect and spatial visualization abilities. Further research with samples representative for the population, conducting both qualitative and quantitative analysis using verified outcome measures and parametric statistics is required to draw accurate conclusions.

A

Development Process

A.1 | Motivation

In this appendix, the development process of the applications used for the study *"The effect of surgical animation on learning anatomy in medical education"* is outlined. These applications[1] were developed for the Microsoft HoloLens® (version 1) and serve as a tool to help students learn the complex three dimensional (3D) anatomy of the musculoskeletal system.

The study conducted in this project focuses on the effect of the surgical animations. These are implemented in two out of these four applications.

Two of them consider the lower extremity, and contain an implemented tibialis posterior tendon transfer case. The other two applications consider the upper extremity, with a pronation osteotomy case. For both extremities, the two applications differ by the presence of an animation of the surgery used to treat the defect (Table A.1).

Table A.1: Overview of the developed HoloLens applications and their implemented scenarios.

	Lower extremity *Tibialis posterior tendon transfer*	**Upper extremity** *Pronation osteotomy*
Intervention case	Default Preoperative Surgical Postoperative	Default Preoperative Surgical Postoperative
Control case	Default Preoperative Postoperative	Default Preoperative Postoperative

[1] In this context the meaning of an application a program designed to fulfil a particular purpose.

The animated surgeries are performed by surgical orthopedists in daily practice and in both surgeries, the dynamical anatomy is altered. In all other regards the applications are identical: both have the same interface and provide visualisation of a default, a preoperative and a postoperative scenario.

Below, first the application requirements are stated, then the tools used for development are listed, followed by a short description of previous work. Finally, the implementations during this research are described, categorized by the software used for development.

A.2 | List of Requirements

After the development, these applications should 1) be compatible with the Microsoft HoloLens (version 1), 2) allow for dynamical assessment, 3) be anatomically correct and 4) be educational and interactive.

Each of these requirements is discussed in detail below.

A.2.1 | Compatible with Microsoft HoloLens 1

2.1.1 The applications should perform at a frame rate of 60 frames per second (fps) (Microsoft, 2021a).

2.1.2 The applications are built on the Universal Windows Platform (UWP) and use the Mixed Reality Toolkit (MRTK).

A.2.2 | Dynamic Assessment

2.2.1 The lower extremity applications should allow for dynamic assessment of dorsiflexion, plantarflexion, inversion and eversion.

2.2.2 The upper extremity applications should allow for dynamic assessment of pronation and supinaton.

2.2.3 Dynamic surgical assessment should be possible for the two applications where a surgery is present.

2.2.4 The student can interact with the application while observing the model from all angles.

A.2.3 | Anatomically Correct

2.3.1 The contents of the application should be anatomically correct.

2.3.2 The range of motion (ROM) of the joints, given a specific scenario, should correspond with the average ROM of the physical body in this scenario.

2.3.3 All objects directly surrounding a rotating joint should move with it accordingly.

2.3.4 Changes in shape of muscle, vascular and nerve tissue during movement should be smooth.

2.3.5 Bones should not be deformed in shape unless part of an osteotomy.

2.3.6 The origin and insertion of tendons should remain at the same location on the bone unless part of a tendon transfer.

2.3.7 Surgical animations should reflect real surgery.

A.2.4 | Educational & Interactive

2.4.1 It should be possible to see the name of an anatomical structure while hovering over the object representing it.

2.4.2 Showing and hiding objects should be possible to allow for interactive visualisation.

2.4.3 Muscle innervation of the large nerves should be implemented.

A.3 | Development Tools

The used development tools are listed below, categorized in software and hardware.

A.3.1 | Software

The software used for the development is:

- Blender version 2.81 *(Blender foundation, Amsterdam, The Netherlands)*
- Unity version 2017.4.18 *(Unity Technologies, San Francisco, California, USA)*
- Windows Software Development Kit (SDK) version 10.0.17134 *(Microsoft, Redmond, Washington, USA)*
- MRTK, version 2017.4.0.0 *(Microsoft, Redmond, Washington, USA)*
- Visual Studio 2017 version 15.9.36 with C# (version 2.10.0) *(Microsoft, Redmond, Washington, USA)*
- Python verion 3.7.4 *(Python Software Foundation, Delaware, USA)*
- Android SDK and Android 10 *(Google, Mountain View, California, USA)*
- Git version 2.27.0 hosted at GitHub *(GitHub, Inc., San Francisco, California, USA)*

A.3.2 | Hardware

The hardware used for the development is:

- Microsoft HoloLens 1 *(Microsoft, Redmond, Washington, USA)*
- Redmi Note 7 *(Xiaomi, Beijing, China)*
- OMEN laptop (with Intel Core i7-8750 CPU @ 2.20 GHz, 2208 Mhz, 6 Cores, 12 Logical Processors) *(Hewlett-Packard, Palo Alto, California, USA)*

A.4 | Previous Work

The Zygote Body developed by Zygote Media Group, Inc. (2017) in cooperation with Google was purchased by the Department of Anatomy of the Leiden University Medical Center (LUMC). With this interactive anatomical atlas as a basis, two new models were created: one for the left lower extremity and one of the right upper extremity.

A.4.1 | Lower Extremity

The lower leg model includes the foot and the structures up to the patella and knee ligaments. It, however, does not include the femur and its surrounding structures (Figure A.1).

Figure A.1: The anatomical model of the lower extremity.

The HoloLens application developed by Bogomolova et al. (2021) called *Dynamic Anatomy* is the starting point for the developments of this study. It was developed using the lower extremity model and allows users to walk around the model to explore it from all possible angles. Furthermore, it is possible to highlight and show or hide specific anatomical structures. These structures are categorized into skeletal, muscular, nervous, vascular and connective tissue and can either be hidden as object alone or by category as a whole. Highlighting structures can be achieved in two manners: either by clicking buttons or by hovering over them while using the Gaze-tool. Using the latter, the structure that is looked at is highlighted while its name is shown just below the cursor. Lastly, the application allows movement for the four basic ankle movements, displayed as 3D animations. These animations are triggered either by clicking a button labelled with the associated movement or by manual movement based on hand gestures. This application did not yet contain the cases nor a surgical animation.

The surgical animation of a tibialis posterior transfer was created by the author during a previous internship.

A.4.2 | Upper Extremity

The arm model consists of the entire right arm and reaches medially up to the jugular vein. It includes the entire scapula and parts of the ribs, but not the sternum, the medial part of the clavicula and the vertebrae. This model reaches caudally until the dorsal part of the ninth rib, including a minor part of the ninth intercostal nerve (Figure A.2).

Figure A.2: The anatomical model of the upper extremity.

There existed no HoloLens application for the upper extremity before the completion of this study. A pronation osteotomy surgery was animated in a previous internship by Judith van der Bie. However, this surgical animation required some alterations, which are discussed in section A.5.2 . Blender (version 2.81, Blender foundation, Amsterdam, The Netherlands) was used for the creating the surgical animations as well as the alterations.

A.5 | Development Steps in Blender

In this section, the development steps in Blender are described, first, for the lower extremity, followed by the upper extremity.

A.5.1 | Lower Extremity

In addition to attempts in previous internships, a new effort was made to improve the surgical animation using the lower extremity model. However, this did not lead to an improved outcome. More details are given in appendix F.

A.5.2 | Upper Extremity

A default, a preoperative and a postoperative scenario were created for the pronation osteotomy case of the upper extremity model. The default and preoperative scenario can be displayed using the same model. This model was made using only the first frame of the animated surgery, while the postoperative model was created by setting the start frame in the timeline after the end of the surgical animation. Additionally, some alterations were necessary for compatibility with the HoloLens and to keep the content anatomically correct. These alterations are described in the sections below.

A.5.2.1 | Decimate

The file size of the upper extremity model was too large to run on the HoloLens. Therefore, the decimate modifier[2] was applied to reduce the file size. In order to link and apply this modifier for every object at the same time, the armature modifier had to be deleted. Then, with one object selected the Decimate modifier was added by clicking Modifiers > Add Modifier > Decimate > Collapse > Ratio > 0.30. Thereafter all objects were selected and the (ctrl + L)-keys were used to link all selected modifiers. Finally, with all

[2]Modifiers are automatic operations that affect an object's geometry in a non-destructive way (Blender, 2021c).

objects still selected Object > Convert to > Mesh from Mesh/Meta/Surf/Text was clicked while in Object Mode to apply all selected modifiers at once.

Decimating resulted in reducing the file size from 41.4 MB to 16.4 MB. For the surgical animation this last step had to be performed for all objects individually, as by the means of preserving the surgical animation, the modifier of the armature should not be deleted nor applied.

A.5.2.2 | Armature

A new armature[3] was added for the non-surgical animation models by clicking Add > Armature. The bones of this armature were created to represent the humerus, radius, ulna and one for the entire hand. The previous model (Figure A.3a) consisted of an armature where big skeletal bones (e.g. humerus, ulna or radius) were made out of up to seven armature bones, while these are supposed to be rigid anatomical bones. Furthermore, the humeroulnar joint was represented by the humerus and the radius instead of the humerus and the ulna. Lastly, the proximal and distal radioulnar joints did not exist, resulting in the radius and ulna being rotated together as one instead of the bones crossing each other when the arm is pronated.

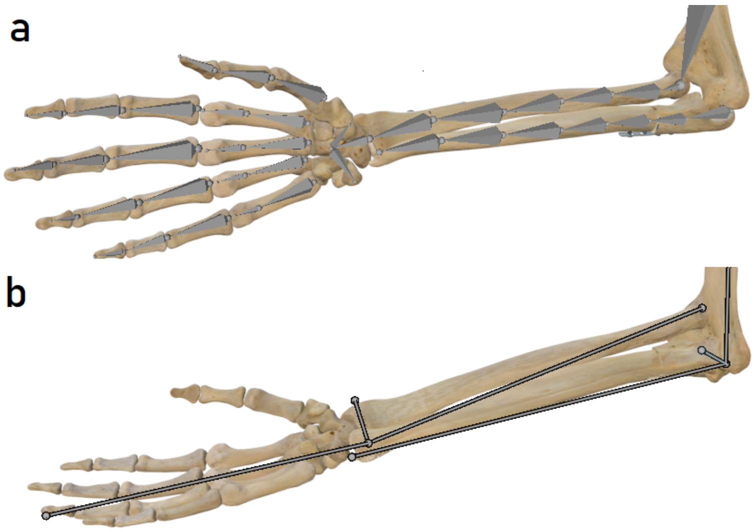


Figure A.3: The armatures of the arm model a) before and b) after representing the anatomical model of the elbow joint.

[3] An armature has the same function as the human skeleton. The armature consists out of bones, which can be individually manipulated. Anything that is parented to the armature will follow the movement of the armature bone(s).

The new armature (Figure A.3b) was made to represent correct anatomical bone and joint movements of the elbow, but oversimplifies the model of the hand. However, for the purpose of this application, the movement of the individual fingers is not required. In this new model, the radius rotates around the ulna. In doing so, the armature bone of the radius was placed on the rotation points, being the middle of the head of the radius proximally and at the distal radioulnar joint. In this manner, the radius rotates around itself proximally while it rotates around the ulna distally. Lastly, the armature bone of the ulna was directly attached to the armature bone of the humerus, to represent the humeroulnar joint, while the armature bone of the radius had an offset to the ulna to ensure correct rotation around the head of the radius.

The armature was parented to all objects by first selecting all objects with A and then the armature with (shift + Left mouse button). Then, Object > Parent > Armature Deform > With Automatic Weights was clicked to parent the objects to the armature. Based on the location of the objects with respect to the armature, the objects are deformed in a similar way as the armature.

A.5.2.3 | Weight Painting

Although automatic weights is a good basis for deforming parented objects, it is not entirely anatomically correct. These automatic weights can be adjusted with weight painting. During weight painting, a colour spectrum is shown from red (indicating maximal influence of the armature bone), to green (indicating medium influence) and finally blue (indicating minimum influence). Each object has its own weight distribution for each armature bone, meaning that one object can be deformed by multiple armature bones with different weight paints over the entire object. The objects that do not move in the desired way can be adjusted using weight paint.

As this model must represent anatomically correct pronation and supination, the objects surrounding the moving joints (being the proximal and distal radioulnar joint) should move accordingly. Therefore, the arm was pronated and supinated 90°.[4] Every muscle in for forearm was controlled with weight painting. Mainly the large muscles towards the fingers were displayed wrong while the arm was pronated. For instance, the Extensor digitorum muscle was going through the ulna when the forearm was pronated 90° (Figure A.4a). This was corrected with adjusting the weight paint of the ulnar and radius armature bones (Figure A.4b), after which the trajectory of the muscle was on top of the ulna as it anatomically should (Figure A.4c). This method was used to adjust

[4]Here the clinical orthopedical degrees are used, not the anatomical ones. Normal anatomical range is 90° supination to 90° pronation, with 0° being the mid-stance.

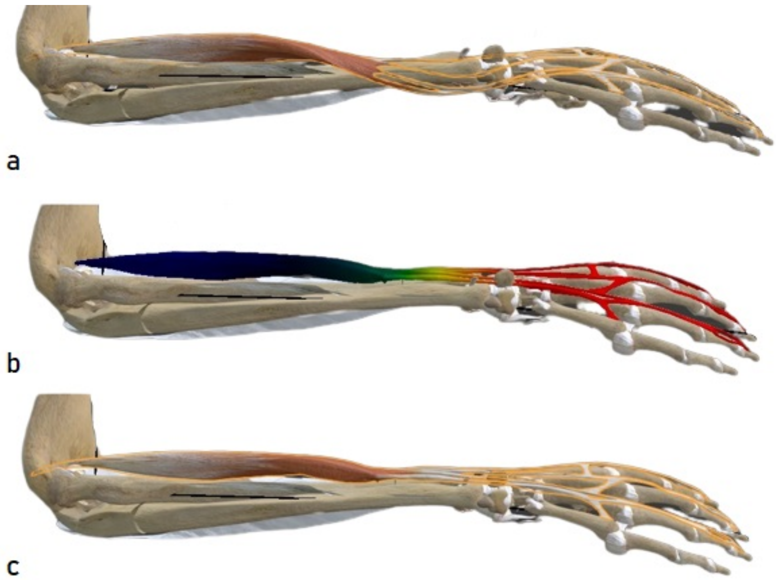


Figure A.4: The lateral side of a pronated right arm showing the extensor digitorum muscle a) before, b) during and c) after weight painting.

objects sticking through other objects, for tendons not being fixated to their origin or insertion and for smoothing objects during movements.

Finally, there were some objects for which weight painting was not a solution. The triceps tendon - for instance - deformed such that it was not possible to restore the anatomical orientation using weight paint. Therefore, the armature was removed as a parent, and the tendon was manually put in the right place. Additionally, the armature was removed for objects which were part of the thorax, as these objects rotated slightly during pronation and supination of the forearm due to the automatic weight paint.

A.5.2.4 | Changing Equipment

The last change that was made to the pronation osteotomy model, were the equipment screws. The four screws placed on each osteotomy site were placed the wrong way round: the compression screws should be placed on the sites where a cortical screw was placed and vice versa (Figure A.5).

A.5.2.5 | Exporting Object Names

In order to name every structure while using the application, the object names were exported along with the collection (e.g. tissue type) it belongs to. To do so, a script (Appendix G) was written in Blender (by using the implemented Python console). The

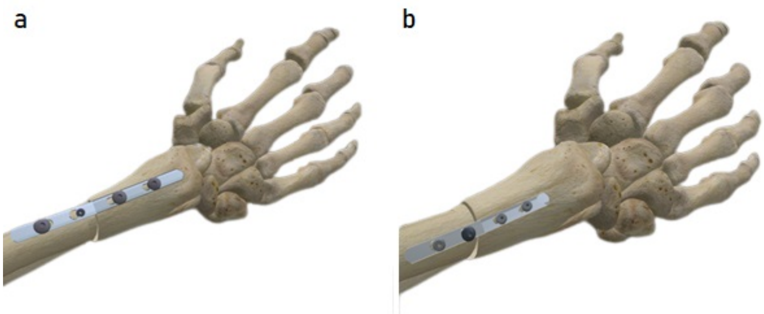


Figure A.5: Right hand after the pronation osteotomy containing a plate and 4 screws. a) the model wrongly consisted out of 3 cortical screws and 1 compression screw. b) the new model with 1 cortical screw and 3 compression screws.

result of the script is a `text(.txt)`-file, containing the name of the selected objects, and the collection it belongs to, separated by a comma. In order to make a complete list, the A-key was hit to make sure every object in the scene was selected.

Next, this `text`-file was loaded into Microsoft Excel and two columns were inserted between the object row and the collection row. The Latin and the English name of the objects was inserted manually in these two columns. As the model of the arm consists out of 296 objects in total, and this is a time consuming manual process, only the most important objects were named, being all bone and muscles together with bigger veins, arteries and nerves and ligaments.

A.5.3 | Export to Unity

Before the export was created, the location, rotation and scale of the objects were applied and all objects were baked to prevent deformed or displaced objects in Unity. To bake an animation, all were selected and click Object > Animation > Bake Action was clicked. For normal objects, Bake Data was set on `Object` gave the best result, while for armatures `Pose` is more fitting.

To export the models from blender to Unity, an Filmbox (FBX)-export was made by clicking File > Export > FBX (.fbx) with having all objects for the export selected. There, the Selected Objects-box is checked, and only the Object types `Armature` and `Mesh` are checked, as the rest is unnecessary for this export. Blender uses a right-handed coordinate system, while Unity uses a left-handed coordinate system. More specifically, in blender, the Z-axis is pointing upwards, while in Unity the Y-axis points upwards. Therefore, in Transform "Apply Scalings" should be changed to FBX Custom Scale. Finally, if the export concerns animations, the Bake Animation box was checked, while leaving all sub-boxes unchecked.

A.6 | Unity

Unity version 2017.4.18 was used through the Unity Hub for the development of the applications. The Git repositories called LUMCHoloLensApp and GyroTest were used as a foundation and for further development[5]. The Mixed Reality Toolkit (MRTK) was used for development for the applications on the Microsoft HoloLens. The main scene was used as a starting point. In this section, the elements within the applications will be explained.

A.6.1 | Import

The FBX-exports from Blender were placed in the `LUMC ▸ Assets ▸ Model`-directory. After that, the Materials of the FBX-file were imported by clicking [Extract Materials...]. Here, the directory containing the materials (`LUMC ▸ Assets ▸ Materials`) is selected. However, this method might not result in the correct materials. In that case, the ○-symbol on the right of [Missing (Object)] can be clicked to select the materials manually. If an animation is imported, this can be checked in the window called [Animation]. Here, the loop animation-box was checked in order to keep on playing the animation instead of only once. Depending on the animation and it's content, some information might not be imported correctly from Blender into Unity. For instance, the transparency and hiding of objects is lost when imported in Unity. Luckily, animations can also be altered in Unity, which is explained in the next section.

A.6.2 | Basic Components

There are several components which can be attached to a GameObject which are essential to understand when working with Unity. These are described in the sections below.

A.6.2.1 | Animations

An animation controller is used to define which animations should play (Figure A.6). The animation shown in orange is playing instantly, and is often idle[6].

[5]Both Git repositories are private and authorisation rights are managed by the LUMC, please contact the authors for access requests.

[6]meaning it is statically passing time without doing anything

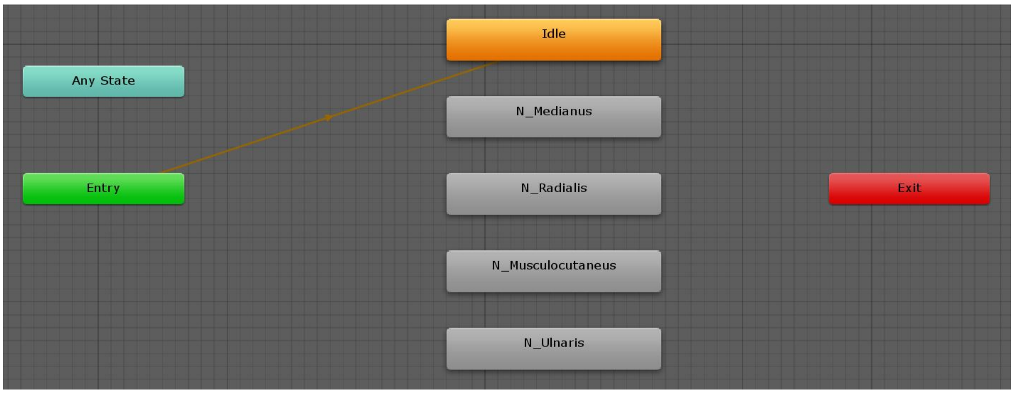


Figure A.6: The Animator window in Unity, with different animations attached to it.

As a gyroscope connected to a smartphone is used in these applications, animations were solely used for animated surgeries and muscle innervation. The animation controller was added as an animator component to the object the animations belong to (Figure A.7).

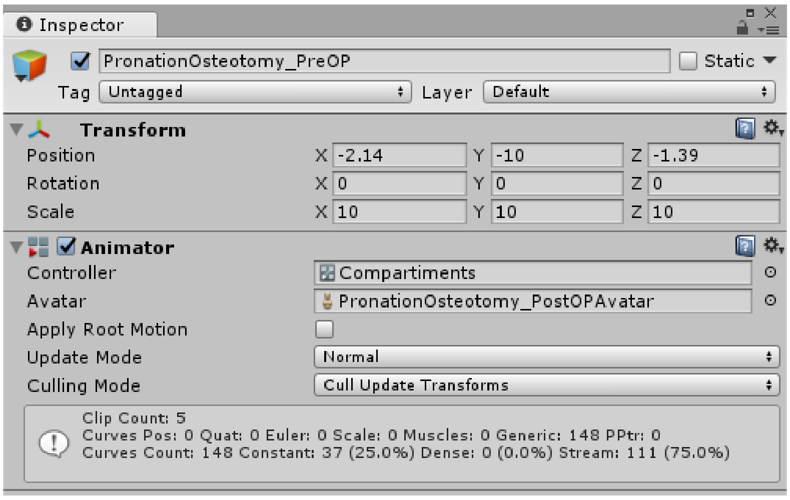


Figure A.7: The Inspector window in Unity containing an animator component, with an animation controller attached.

Animations can either be made in Blender's animation window or in Unity using the record-button in the animation window. If an Animation Controller is attached to the model, the alterations that are performed can be recorded using the Animation window. Here, keyframes can be implemented after which automatic interpolation based on Euler Angles or Quaternions is performed for the frames in between (Figure A.8).

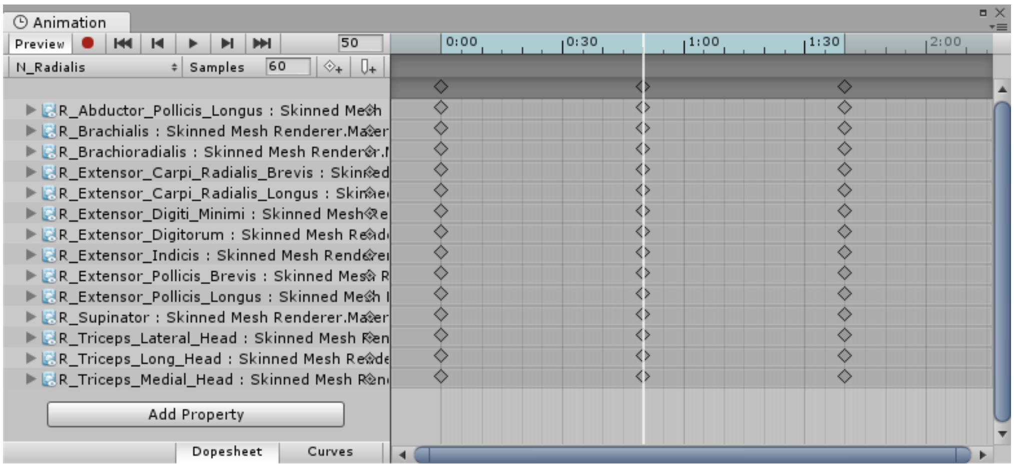


Figure A.8: An animation in Unity to highlight the muscles innervated by the *n. radialis*. The animation was created by using the Record-button on the top left of the animation window.

A.6.2.2 | Buttons

The Button GameObject contains a `Button (Script)` component in the Inspector. Here, one or more `On Click`-event(s) can be assigned with + (Figure A.9). The GameObject to which the action should be applied is attached to this `On Click`-event. Different options can be selected dependent on the components that the selected object contains. Buttons are commonly used to start animations. For this, the object that is dragged to the `On Click`-event is required to have an Animator component (Figure A.9).

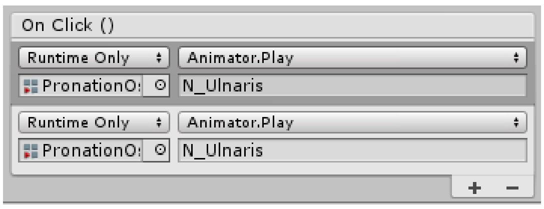


Figure A.9: On Click-event(s) in the inspector window.

A.6.2.3 | Dropdown Menu

A dropdown menu allows the user to choose one value from a list. In these applications, a dropdown menu is used to switch to a different scenario. Changes based on which option of the dropdown menu is selected can either be implemented by the `On Value Changed`-panel or through a script.

A.6.2.4 | Toggles

Toggles are a valuable tool when an option or an object should be switched on or off. A checkmark is seen when the toggle is on, and an empty box is displayed when the toggle is off. A toggle is used in these application for showing the muscle innervation animations and for enabling the gaze-tool.

A.6.2.5 | Canvas

A canvas is used to attach User Interface (UI) objects to. Other objects should be parented to the canvas and displayed within the Canvas borders in the Scene View.

A.6.3 | Implementing Gyroscope Data

The gyroscope of an Android smartphone was used for manipulation of the target joints in the upper and lower extremity models, after which these follow the movement of the smartphone. To achieve this, an Android application was made with Unity and sharing abilities were implemented into the main scene for full functionality.

A.6.3.1 | Android Application

The Git repository `GyroTest` was used to built an Android application which gives access to its gyroscope data. The Build Settings in Unity were set to Android by clicking File > Buildsettings > Platform > Android. The `TestMultiplayer\_kopie\_U2017\_Android` repository already contained an Android application, through which a host session could be searched based on the HoloToolkit example `SharingWithUNET`. After connection to the host, a red cube is spawned into the Android application which can be manipulated using the gyroscope of the smartphone.

The problem was, however, that this gyroscope worked in the World-coordinate system, while a local-coordinate system is desired for the purpose in these applications.

The coordinate system

By using the world-coordinate system, the movement is influenced by the cardinal direction the smartphone is directed in. This, for instance, results in a dorsiflexion when the user is facing north, but an inversion when facing east. The user, therefore, cannot use the application when walking around the model, as the transformation of the joints changes when pointed a different cardinal direction. Thus, the functionality of this Android application was altered to a local coordinate system.

Implementation of a local-coordinate system

This was achieved by changing the script called `GyroControlCubeCalibrated` in the `TestMultiplayer_kopie_U2017_Android` ▸ `Assets` directory. In this script, a reference rotation is set at the start, defined by the inverse quaternion[7] from the attitude of the gyroscope at the start. This reference rotation results in an opposite rotation compared to the rotation of the gyroscope and is used to reset the starting rotation.

The raw gyroscope data is continuously updated and multiplied with the reference rotation to make the rotation relative to the current rotation rather than the world. The result rotation is then multiplied by the inverse quaternion of the z-axis, to reverse the rotation around this axis. The orientation of the positive x, y, and z axes for a typical Android smartphone are displayed in Figure A.10.

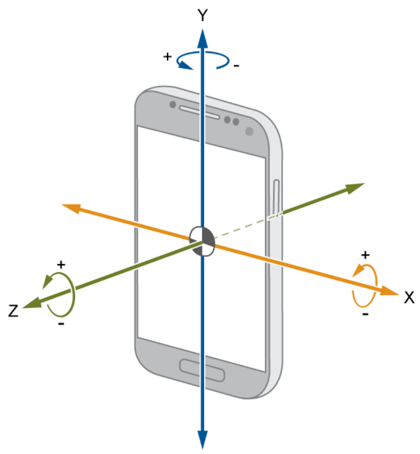


Figure A.10: Orientation of X, Y and Z axes for an Android mobile phone (MathWorks, 2021).

Build

The Android application was build by clicking File ▸ Build Settings... ▸ Build. The name of the application can be changed while clicking Player Settings.... This results in an Android Package (APK), which can be installed on any Android smartphone set in developer mode. However, the application is only useful, if a gyroscope is implemented in the smartphone.

A.6.3.2 | Implementing Sharing Abilities into Main Scene

The Android application previously discussed serves as client, for which the HoloLens is the host. These two devices can pair when connected to the same Wi-Fi network.

[7]Quaternions, along with their advantages compared to Euler angles are discussed in section A.6.3.3.

To function, several UNET prefabs were added to the `Managers` GameObject in the main scene. The `UNETAnchorManager` prefab was added as a child to the Managers GameObject in the main scene. This prefab is found in the directory named `Assets` ▸ `UNET SolutionUWP` ▸ `HoloToolkit-Examples` ▸ `SharingWithUNET` ▸ `prefabs`. Furthermore, the `UNETSharingStage` GameObject was added. This GameObject has two components: `Network Manager (script)` and `Network Discovery With Anchors (script)`. The first is implemented in Unity itself and latter is found in the `Assets` ▸ `UNET SolutionUWP` ▸ `HoloToolkit-Examples` ▸ `SharingWithUNET` ▸ `Scripts` directory. Lastly, the component called `WorldAnchorManager` was added to the Manager GameObject in the main scene. This script is found in the `Assets` ▸ `HoloToolKit` ▸ `Common` ▸ `Scripts` directory.

A.6.3.3 | Align Joint Rotation with Gyroscope Rotation

At this stage, both devices can communicate with one another, but the model is not manipulated by the gyroscope yet. Therefore, the `GyroControlCubeCalibrated` script[8] in the `Assets` ▸ `UNET Solution UWP` directory was altered. The Euler angles (called `vector3` in Unity) that were used to manipulate the joints, introduced several problems during rotation. Quaternions have numerous advantages over Euler angles. Both are discussed in the paragraphs below.

Euler Angles

Euler angles use a series of three subsequent rotations about three mutually orthogonal axes in space. Although Euler angles are the most commonly used method to describe orientations in space and is generally the best understood by humans, it gives rise to several problems.

The first problem is the ambiguity of Euler angles, meaning the same rotation can be obtained with different sets of Euler angles (van Dam and van Dam, 1990). This phenomenon is shown in Figure A.11, where the orientation of a guitar is represented by three different sets of Euler angles. Although A.11b and A.11c are the result of different sets of Euler angles, their orientation in space is equal. In fact, this orientation can be achieved by even more sets of Euler angles.

A second problem is that using Euler angles, the resulting orientation depends on the order in which the three rotations are performed. Using a different sequence of rotations, the same Euler angles can represent different orientations in space. In practice, this is prevented by performing the three rotations in a fixed order.

[8]Not to be confused with the script in the GyroTest Git repository, having the same name...

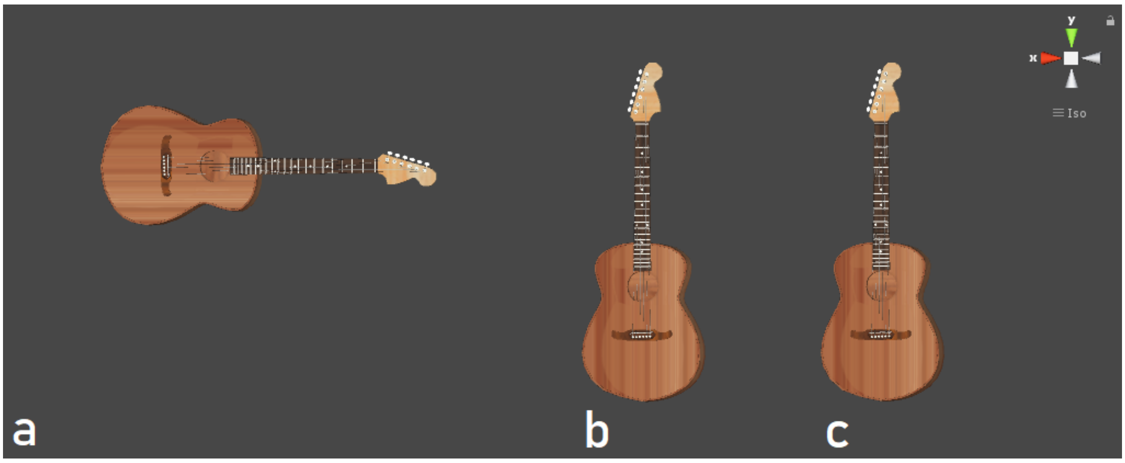


Figure A.11: A guitar shown with different orientations. In a) the orientation is the result of Euler angles $[0, 0, 0]$ with dimensions $[x, y, z]$, in b) $[0, 0, 270]$ and in c) $[180, 180, 90]$. It is clear that although b) and c) are represented by different sets of Euler angles, their orientation in space is the same.

A third problem is that when using Euler angles, a series of rotations can result in one degree of freedom being lost, a situation called gimbal lock. This phenomenon shows the singularity of Euler angles, and occurs when the matrix is rank deficient. As a result, two rotation axes share the same plane. A rotation is then only dependent on the difference between the two angles, as changes of the two gimbals on the same plane result in rotations around the same axis (Dam et al., 1998).

This clearly explained by Silke (2009) in Figure A.12, with an arrow shown in three dimensional space. The three gimbals are colored green, red and blue and are parented in the same manner[9]. If - after a series of rotations - two gimbals share the same plane, their rotation axis is similar (Figure A.12a). In the case that the animation in Figure A.12a is continuing with displaying an horizontal arrow, there is no a direct axis to rotate. In that case, all three axis need the be rotated in order to obtain the desired orientation (Figure A.12b). However, as seen by the yellow arc in Figure A.12b, this series of rotations causes the tip of the arrow to follow a curved path rather than a path straight down. This phenomenon can affect animations.

A fourth problem is the wrap around using Euler angles. Euler angles in Unity are defined from $-\pi$ to π. When rotating clockwise from 0 to $+1.1\pi$, Euler angles show a counterclockwise rotation from 0 to -0.9π. Even worse, when slightly osculating from, for instance, 0.9π to 1.1π, Euler angles oscillate all the way from -0.9π to $+0.9\pi$ instead.

[9] If the green gimbal is rotating, the entire system follows. If the red gimbal is rotating, only the blue gimbal and the arrow are rotating, and finally if the blue gimbal is rotating, only the arrow follows.

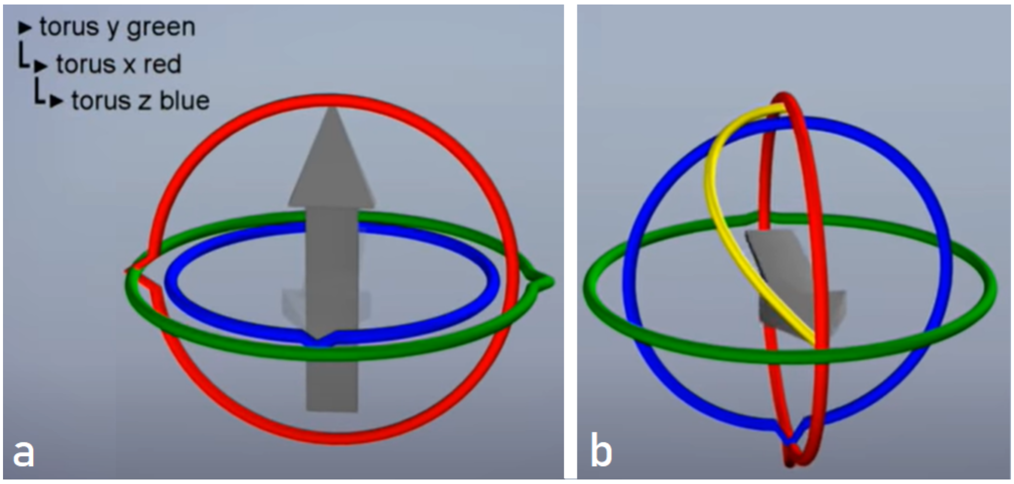


Figure A.12: Gimbal lock explained by Silke (2009). In a) the parenting structure is shown: rotation of the green torus (gimbal) results in the entire system to rotate, the red torus rotates the blue torus and the arrow and the blue torus rotates only the arrow. When two tori share the same plane, gimbal lock occurs. This is a phenomonon where one degree of freedom is lost, as two tori share the same rotation. b) the desired rotation can be achieved by a series of rotations. However, the tip of the arrow will follow the yellow arc rather than going straight down.

Euler angles then result block-pattern, whereas quaternions are a smooth continuous function(shown in Appendix H).

Moreover, Unity does not store rotations as Euler angles, but purely represents them for easy interpretation essentially by using a conversion function from quaternion to Euler, giving multiple solutions in Euler angles for the same quaternion (Unity Documentation, 2021).

Quaternions

Quaternions are a four dimensional vectors, which express orientation. Eulers Rotation Theorem (Euler, 1776) states that any attitude of a rigid body can be represented with a rotation axis ($\mathbf{n}$) and a rotation (θ) around this axis. An example is shown in Figure A.13. The gray arrow presents the axis of rotation. The rotation around this axis is visualised by the three dots on sphere surface. Mathematically the relation between this configuration and the associated quaternion is:

$$q := \begin{bmatrix} w \\ x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos(\theta) \\ \sin(\theta)n_x \\ \sin(\theta)n_y \\ \sin(\theta)n_z \end{bmatrix}$$

Note that the three components n_x, n_y, n_z constitute the components of the rotation axis $\mathbf{n}$.

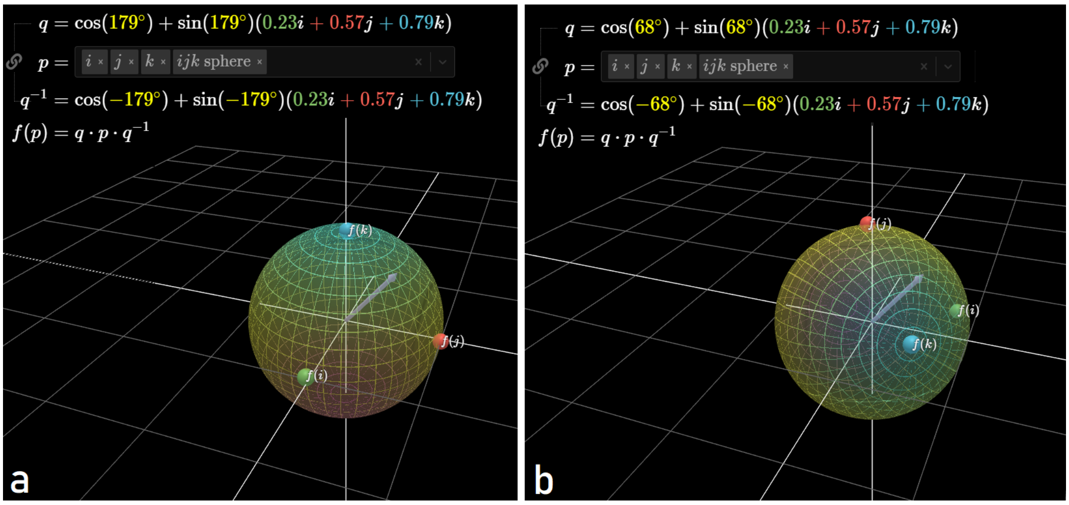


Figure A.13: Visualizing quaternions by Eater and Sanderson (2018). The axis of rotation is represented by $\mathbf{n}$ (the gray arrow). The rotation around this axis of rotation is represented by θ (the three dots on the sphere surface). Visualized by altering θ from $-179°$ to $-68°$. Note how the three dots on the sphere are rotated around the axis of rotation.

Quaternions do not have the problems Euler angles have: one orientation can only be represented by one certain orientation in space. Every orientation can only be described by two opposite quaternions ($q_1 = -q_2$).

In the example in Figure A.11, both the orientation in A.11b as in A.11c have a quaternion with components $[0, 0, -0.7071, 0.7071]$ with dimensions $[x, y, z, w]$[10].

In practice, a quaternion is always a unit quaternion, which has a magnitude of 1. The magnitude can be calculated with the dot-product of the quaternion with itself. A quaternion is normalized by dividing every component of the quaternion with the magnitude. Not using the unit quaternion can lead to undesired animations[11].

[10]Unlike the rest of the world notating quaternions as [w,x,y,z], Microsoft and Unity use a different notation.

[11]In my case, a foot acting as if it was a the propeller of a helicopter.

Implementation transformations with Quaternions

In the *GyroControlCubeCalibrated.cs* script, the joints were transformed based on player rotation (the player being the red cube shown on the connected smartphone). For each joint, the physiological ROM was notated in quaternions based on the Euler angles shown in the inspector[12]. The maximal and minimal values of the ROM were set for the default, preoperative and postoperative scenarios such that if the rotation with the smartphone is greater than the ROM, the maximal rotation in that direction is shown instead. Quaternion multiplication was used to make the current rotation relative to the starting position of the joint.

For the postoperative situation of the tibialis posterior tendon transfer case, a plantarflexion movement should be the result of a rotation around the x-axis of the phone, while a dorsiflexion should be the result of a rotation around the y-axis of the phone. However, dorsiflexion and plantarflexion usually are a result of a rotation about the same axis. the postoperative situation was implemented in this manner to represent that an inversion results in a dorsiflexion right after surgery, before the plasticity of the brain causes this effect to fade.

Because *Quaternion.normalize* was not yet available using Unity 2017.4, this method was added to the *GyroControlCubeCalibrated.cs* script manually from the Git repository of Unity Technologies (2021). Furthermore, because the new rotation is applied to the local start rotation, the start rotation should be on the left hand side and the new rotation on the right hand side of the Quaternion multiplication matrix. Using *Quaternion.operator* * function implemented in Unity, lead to wrong rotations. Therefore, this operator was also added manually to the same script from the same Git repository mentioned before.

Assigning the joints

The GameObjects representing the joints, were assigned by dragging it to the component called `LUMCModelSync` of the `ModelSync` GameObject. For the lower extremity, *Virtual Skeleton_Bone_1* and *_Bone_2* were defined to represent the tibiotalar joint (`Bone.001`) and the talocalcaneal joint (`Bone.002`) respectively. The upper extremity only requires the one bone to be assigned as the proximal radioulnar joint and the distal radioulnar joint rotate together.

[12]The Euler angles were solely used to obtain the quaternions corresponding with the maximal joint rotation, which is defined in degrees.

Determining the axis of rotation
To know which axis of the `Bone` GameObject performs which rotation, the axes orientation of the specific joint should to be taken into account. In Figure A.14, the axis orientation are shown for the tibiotalar joint in A.14a and the talocalcaneal joint in A.14b. Furthermore, the axis are oriented differently in the two bones. The tibiotalar joint should make dorsiflexion and plantarflexion, which is the result of a rotation around the x-axis (shown in red). The talocalcaneal joint facilitates inversion and eversion, which is the result of a rotation around the y-axis (shown in green).

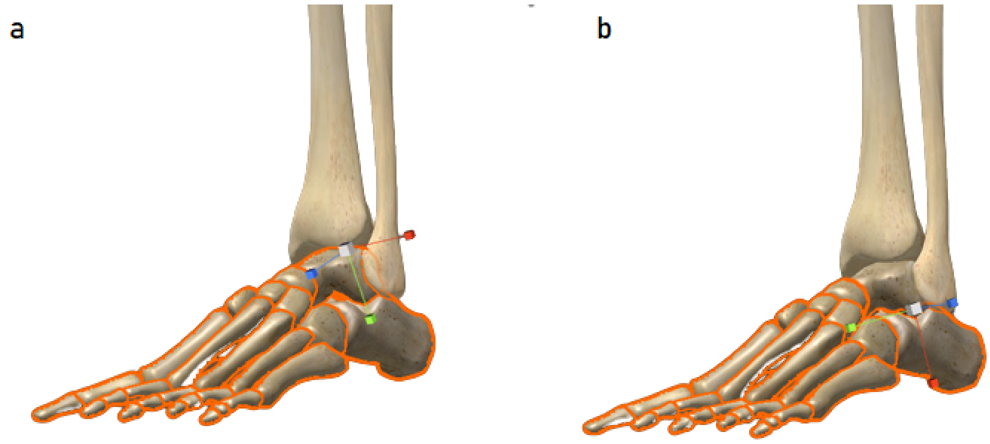


Figure A.14: Axes orientation of a) the tibiotalar and b) the talocalcaneal joint. In a) a rotation around the x-axis (shown in red) results in plantarflexion and dorsiflexion and in b) inversion and eversion are a result of a rotation around the y-axis (shown in green).

For the upper extremity, the axis of the proximal radioulnar joint is shown in Figure A.15. Rotation around the y-axis results in pronation or supination. Note that the y-axis is in the exact same direction as the radius. This was achieved in Blender because the axis orientation in Unity cannot be changed without changing the entire model. An offset in axis alignment to the desired rotation will result in unnatural movements.

Finally, no animation component with joint rotations should be included in the models manipulated by the gyroscope, as in the current state of development this animation overrules all gyroscope transformations. Currently, the joints are manipulated such that the hologram will act as a mirror when the smartphone is held in the left hand.

A.6.4 | Changes to the Main Scene

The title of the application together with a small explanation and the included scenarios were displayed on the registration screen. In order to start a host session, the

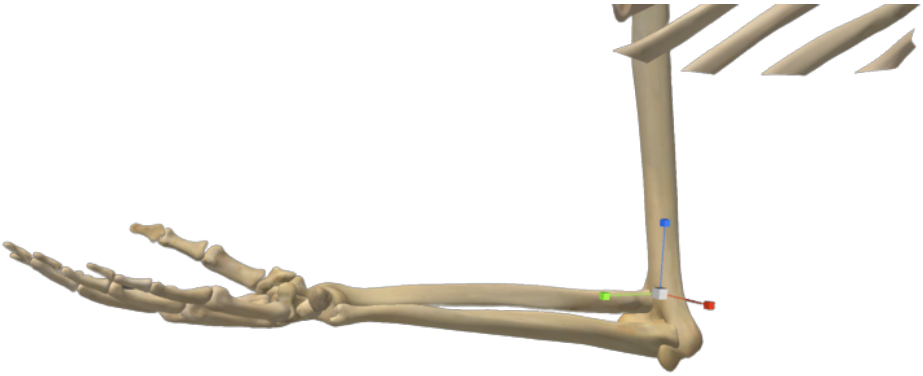


Figure A.15: Axes orientation of the proximal radioulnar joint. Rotation around the y-axis (shown in green) results in pronation or supination.

`StartSesstionButton` script was added a button on this screen.

A.6.4.1 | Scene Showing the Upper Extremity

To create the upper extremity applications, the default and case model showing a pronation osteotomy were added to the scene instead of the lower extremity models. The Excel export containing the GameObjects, their Latin and English name and its tissue type (category) was added to the `Data Provider` component of the GameObject called `Managers`.

On top of decimating this model (reducing the mesh size, described in section A.5.2.1), the maximal size of the textures had to be reduced in size from 2048 to 512 in order to make the model compact enough to run smoothly on the HoloLens (Hensen et al., 2021).

A.6.4.2 | Managing Button Visibility

The `DataProvider.cs` script was edited for all applications such that the category (tissue) buttons did not longer ignore objects without a given Latin name in the `Layer.txt`-file. However, this resulted in empty individual buttons for objects without an assigned Latin name. Therefore, the `LUMCSceneManager.cs` script was altered. Buttons are created automatically in this script. Empty buttons were prevented by adding an if-statement which only creates the button if the Latin name of the GameObject was not empty.

In this manner, an entire layer (e.g. skeletal, muscular, nervous, vascular or connective tissue) is hidden as a category, although not every GameObject belonging to that layer can be hidden individually. This saves a lot of time determining the Latin and English names for all 296 objects in the model of the upper extremity. Additionally, for both the upper extremity and the lower extremity, this allows for making a selection of object names for which a button appears based on its importance for the specific objective.

A.6.4.3 | Muscle Innervation of the Large Nerves

An Animator called `Innervation` was made, to which animations of the large nerves were added. These animations were created through recording in Unity's animations panel. With the recording button on, a keyframe on frame 50 was inserted where the muscles innervated by the specific nerve were highlighted. When two keyframes on frame 0 and 100 are inserted with the normal muscle color, automatic interpolation causes the highlight of the muscle to fade in and fade out. Buttons were created for each large nerve, and animations could be initiated though an `On Click`-event. These buttons automatically appear when the toggle to highlight innervation is on.

A.6.4.4 | Added Scenarios

In the `LUMCSceneManager.cs` script, the different scenarios were added based on the application type (e.g. intervention or control). If the surgery scenario was selected, the Play, Pause and Stop-buttons were displayed automatically, while the innervation, the layer categories and layer buttons were hidden.

A.6.5 | Build

Before the build was made, the Default model was displayed in the Scene. The Surgery model (if applicable) and the case model were made invisible in the scene with the toggle in the Inspector. The `RegistrationScreen` and `IngameMenu` GameObjects were also toggled off. With these settings, the right GameObjects load or unload automatically in play mode. The application was build with File > Build Settings.... There, the Add Open Scenes-button is clicked, after which the current scenes are displayed and selected in the `Scenes In Build` window. The `Universal Windows Platform` was selected in the `Platform` window and the `Target Device` was set to HoloLens. Furthermore, the `Build Type` was set to D3D, both the `SDK` and `Visual Studio Version` were set on Latest installed and `Build and Run on` was set to Local Machine. In Player Settings..., the `Product Name` was changed dependent on the specific application. The application icons were changed to display the following:

- A - Tibialis posterior tendon transfer case, including surgical animation
- B - Tibialis posterior tendon transfer case, excluding surgical animation

- C - Pronation osteotomy case, including surgical animation
- D - Pronation osteotomy case, excluding surgical animation

There are a lot of different slots to display icons, which should all have the pixels determined by the slot[13]. The minimal Logo tiles that should be changed to show a different icon in the applications menu on the HoloLens are the following:

- Square 44×44 Logo – Scale 200% (88×88 pixels)
- Square 71×71 Logo – Scale 200% (142×142 pixels)
- Square 150×150 Logo – Scale 200% (300×300 pixels)
- Square 310×310 Logo – Scale 200% (620×620 pixels)

Thus, "A", "B", "C" and "D" icons were created and added to all these logo slots. To enable sharing between the HoloLens and the Android application, the `InternetClient`, `InternetClientServer` and `SharedUserCertificates` toggles were checked in the capabilities window (Player Settings > Publishing Settings > Capabilities). Back in the main build window (`Build Settings`), the Build-button was clicked. An `App` directory was made where the build for each application was saved. This generates a Visual Studio solution (`.sln`) file in the chosen directory with the name of the application. This file was opened with Microsoft Visual Studio, and a Microsoft HoloLens attached to the computer with USB. Using the top toolbar in Visual Studio, the target was changed from Debug to Release and from ARM to X86. Then the arrow next to Local Machine-button was clicked and the deployment target was set to Device. To deploy the solution to the HoloLens, Build > Deploy Solution was clicked. Now the application is ready to use on the HoloLens. In the case that it is the first time deploying to the device, the computer has to be paired with the HoloLens beforehand, using Visual Studio (Microsoft, 2021c).

A.7 | Review of Requirements

In this section, the requirements listed in section A.2 are reviewed to give an overview of the requirements that were met in the current development process and to list those that still need to be improvements.

[13] Making it impossible to drop a (88x88 pixels) logo in any other slot than (88x88 pixels).

A.7.1 | Compatible with Microsoft HoloLens 1

All applications could run on the HoloLens, although for the applications concerning the upper extremity, an acceptable performance was only reached after certain measures to reduce the file size. In Blender, the Decimate modifier was used to reduce the Mesh-size (section A.5.2.1). Similarly, the textures were reduced in size in Unity (section A.6.4.1). Although these means made it possible to run the application concerning the pronation osteotomy case, it still resulted in a jittery screen upon start and while loading new models. This is resolved after the model is loaded properly, which usually takes roughly 5 seconds.

Although the models in the applications concerning the tibialis posterior tendon transfer loaded quickly, it was not achieved to play the surgical animation at a frame rate of 60 fps. Suggestions for further attempts are given in appendix F.

A.7.2 | Dynamic Assessment

Dynamic assessment of the joint movements is possible through using the gyroscope via the Android application. Alterations in this development process allowed for observation from all angles by modifying the Android application from world-space to local-space (section A.6.3.1). Both surgeries can be viewed while walking around the model, during which the menu can still be used.

A.7.3 | Anatomically Correct

Although objects surrounding a rotating joint mainly followed accordingly by using automatic weights on the armature, manipulations using weight paint were inevitable to adjust for anatomically incorrect tissue (section A.5.2.3).

The implementation of a gyroscope allowed manipulation of the joints with limitations based on the ROM for a given scenario and joint (section A.6.3.3). To acquire a correct surgical animation, the inserted screws in the pronation osteotomy case were corrected (section A.5.2.4).

A.7.4 | Educational & Interactive

The feature to show the object name while hovering over it was already implemented in previous development. It, however, resulted in some difficulties for the current applications. Changes made during this development process were the implementation of the labeling the upper extremity (sections A.5.2.5 & A.6.4.2) and the possibility to make a selection of the objects containing a button (section A.6.4.2). Muscle innervation of the large nerves was implemented in all applications (section A.6.4.3).

A.8 | Limitations and Future Work

Limitations of the current applications are listed in this section along with recommendations for future development.

A.8.1 | Version Incompatibility

Version 2.81 from Blender and Unity 2017.4 do not compatible with one another as is the case in other version combinations. If Blender version 2.79 was used with Unity 2017.4 instead, the files could be imported directly from the Blender (.blend) file. This solution might allow for a smooth tibialis posterior tendon transfer animation, discarding the stop motion animation. Moreover, exporting from Blender to Unity would be easier in general, and changes in the Blender file would automatically be implemented in Unity. A downside however, is that a Blender file commonly is quite large, making it less suitable to share over Git. Downgrading a single blender file from version 2.81 to vresion 2.79 was not successful and upgrading Unity to a newer version, resulted in loss of MRTK functionalities. It is recommended to upgrade Unity and all necessary packages, to make it compatible with a newer Blender version. This is especially the case, as the current Unity software is 5 years old today, making it prone to bugs, poor performance, lost data, and - as mentioned - incompatibility (Navarro, 2021).

A.8.2 | Lost Functionalities in the Development Process

Although the new applications were build using the foundation of a working application, some software bugs appeared in the latter. For instance, the anatomical structure buttons crashed sometimes, making it impossible to use this functionality. A partial solution was found by ensuring that all the object names of the `layers.csv` file were identical to the object names in Unity. However, the crash still occurred occasionally, to which a plausible cause could be that two buttons were hit at once when the cursor was not placed entirely on one button.

Another functionality that was lost in the development process was the voice control. This was working as it should in the version used as foundation, but the functionality did not work any longer after all changes were implemented. However, based on the changes made during further development, both of these errors should not occur.

The cause to these failures is still unknown. One assumption for these error is lost data or a poor performance due to outdated software, as mentioned in the section before. By any means, it is recommended to clean the Git repositories, to keep it orderly. Right now, there are many branches that are simply unused and even more directories that contain unnecessary files. Even more so, the names of some directories and scripts are duplicates or named very cryptic, resulting in confusion.

A.8.3 | Data Extraction

With the current state of development, the feature to extract data in a log-file was not yet updated. With this feature, the buttons that users clicked could be logged and used for interpretation of the results. As of now, it remains unknown to the researchers whether a user accessed all scenarios implemented in the applications.

A.8.4 | Connectivity

In the Android application, only the first slot is shown, meaning that if more HoloLenses would host over the same Wi-Fi network, their buttons would overlap. This was resolved in the current research by using different Wi-Fi networks based on a hotspot set up by the paired smartphone. However, placing a new host automatically one slot down resolves these issues. For future development, an interesting implementation would be the connectivity of different HoloLenses with one another to allow users to study together.

A.8.5 | Performance

As mentioned in section A.5.1, the current approaches to improve the animation of the tibialis posterior tendon transfer were not successful. In future work, a script could be written to synchronize the script managing the FBX rendering for each frame for the objects containing the curve modifier with the another animation containing the rest of the surgery.

A lack of performance is also noticeable while loading a new model in the upper extremity applications. To prevent a jittery screen during loading, the decimate modifier could be used once more in Blender, although one should be careful not to lose anatomical structures with using this modifier. Another possibility would be to reduce the model to reach only up to for instance the humerus, although excluding the plexus brachialis results in loss of essential information regarding innervation.

A.8.6 | Anatomically Correct

Despite the endeavours in the current development, the upper extremity model still contains some incorrect anatomy. When broadening this model with more joints using current methods, it is expected that anatomical mistakes will occur so frequent that the application is not longer suited for medical education. To overcome this during future development, the physics modifier could be implemented in the model in Blender. Using this modifier, collisions of - for instance - muscle and bone tissue could be prevented (Blender, 2021a). Furthermore, force fields could be explored to anchor tendons and ligaments to bone tissue (Blender, 2021b).

B

Learning Objectives and Instructions

B.1 | Tibialis Posterior Tendon Transfer case

B.1.1 | Learning Objectives

At the end of the learning session, students should be able to:

1. Identify the following bones of the lower leg, ankle and foot:
    - Tibia
    - Fibula
    - Talus
    - Calcaneus
    - Medial cuneiform
    - Lateral cuneiform
2. Indicate for both the tibiotalar and subtalar/talocalcaneal joints which of the following movements they facilitate
    - Dorsiflexion
    - Plantar flexion
    - Inversion
    - Eversion
3. Determine which muscles are affected by a peroneal nerve injury and which movements of the ankle and foot (dorsiflexion, plantar flexion, inversion and/or eversion) are lost.

4. Determine the course of the tibialis posterior muscle and indicate which movements it induces during contraction. This is determined by it origin and insertion, and by its course with regard to the joint axes and its surrounding structures.
5. Determine which movements of the ankle and foot in a patient with a peroneal nerve injury gains and loses after the posterior tibial tendon transfer surgery.
6. Determine the advantages and disadvantages of a tibialis posterior muscle transfer for a patient with a peroneal nerve injury in terms of basic activities. In other words: which basic activities is a patient able to do (better) after surgery and which not any more (or worse)?

B.1.2 | Instructions

1. Identify the relevant bones.
2. Identify the *tibiotalar joint* (ankle joint, between tibia and talus) and the *subtalar or talocalcaneal* (foot joint, between talus and calcaneus) joints. Note that both joints have their own unique joint axes, and they determine the motion patterns together with the origin, insertion, and course of the muscles.
3. Identify the following muscles and their function, which are innervated by branches from the common peroneal nerve:
   - Extensor digitorum longus muscle
   - Extensor hallucis longus muscle
   - Peroneus brevis muscle
   - Peroneus longus muscle
   - Tibialis anterior muscle
4. Identify the tibial nerve, which innervates the tibialis posterior muscle.
5. Identify the tibialis posterior muscle preoperatively and determine its function.
6. Identify the tibialis posterior muscle postoperatively and determine its function.

B.2 | Pronation Osteotomy case

B.2.1 | Learning Objectives

1. Identify the following bones of the arm:

- Humerus
- Radius
- Ulna

2. Indicate how the proximal radioulnar joint facilitates the following movements:
    - Supination = flat of the hand (handpalm) is facing upwards when the hand is laying on a table
    - Pronation = flat of the hand (handpalm) is facing downwards when the hand is laying on a table
3. Determine the following muscles including their normal trajectory, function and innervation:
    - Pronator teres muscle
    - Pronator quadratus muscle
    - Supinator muscle
    - Biceps brachii muscle
    - Brachioradialis muscle
4. Determine which muscles are injured with a defect between C6 and T1 and which movements of the forearm (pronation and/or supination) are lost.
5. Determine the movement of the radius and ulna and indicate how an imbalance between the pronator muscles and the supinator and biceps muscles can occur.
6. Determine the advantages and disadvantages of a pronation osteotomy for a patient with an injury between C6 and T1 in terms of basic activities. In other words: which daily activities is a patient able to do (better) after surgery and which not any more (or worse)?

B.2.2 | Instructions

1. Identify the following bones of the arm:
    - Humerus
    - Radius
    - Ulna

2. Identify the proximal radioulnar joint and how supination and pronation are induced by the radius and ulna.

3. Identify the following muscles and their function, which are innervated by the following spinal cord segments:

   - Innervation from C6, C7, C8 and T1
     - Pronator teres muscle (C6 / C7)
     - Pronator quadratus muscle (C8 / T1)
   - Innervation from C5, C6, C7, C8 and T1
     - Supinator muscle (C7 / C8)
     - Brachioradialis muscle (C5 / C6 / C7)
   - Innervation from C5, C6 and C7
     - Biceps brachii muscle (C5 / C6 / C7)

4. Determine why there is an imbalance between the pronation and supination muscles preoperatively for a patient with an injury between C6 and T1.

5. Identify the relative position of the ulna and radius postoperatively and determine the result in function.

C

Anatomical knowledge test

C.1 | Tibialis Posterior Tendon Transfer case

Anatomical knowledge test

Fill in your number here

Posterior tibial tendon transfer

The questions in this anatomical test are regarding a tibialis posterior muscle transposition where the muscle is transferred from its original insertion towards the dorsal side of the foot.

1. What are the main movements induced by the posterior tibial muscle **before** the surgery?
   - ☐ Inversion
   - ☐ Eversion
   - ☐ Dorsiflexion
   - ☐ Plantarflexion

2. Which muscle does the m. tibialis posterior replace in terms of functionality **after** surgery?
   - ☐ Extensor digitorum longus muscle
   - ☐ Extensor hallucis longus muscle
   - ☐ Flexor digitorum longus muscle
   - ☐ Flexor hallucis longus muscle
   - ☐ Gastrocnemius medialis muscle
   - ☐ Gastrocnemius lateralis muscle
   - ☐ Peroneus brevis muscle
   - ☐ Peroneus longus muscle
   - ☐ Soleus muscle
   - ☐ Tibialis anterior muscle

3. What are the main movements induced by the posterior tibial muscle **after** the operation?
   - ☐ Inversion
   - ☐ Eversion
   - ☐ Dorsiflexion
   - ☐ Plantarflexion

4. Indicate with a [x] whether the muscles are innervated by the peroneal or tibial nerve.

	n. tibialis	**n. peroneus**
m. peroneus longus		
m. flexor hallucis longus		
m. tibialis anterior		
m. tibialis posterior		

5. Give an example of a change in different gait patterns that the patient was able to do **preoperatively** but has difficulty with **postoperatively** (after being fully recovered from the surgery).
   - ☐ Normal gait
   - ☐ Gait on heels
   - ☐ Gait on toes
   - ☐ Gait on soft sand or gravel
   - ☐ Gait on a straight line (koorddansersgang)

6. Give two examples of a change in different gait patterns that the patient was **not** able to do **preoperatively** but is able to do **postoperatively** (after being fully recovered from the surgery). **Explain why.**

   1)____

   2)____

C.2 | Pronation Osteotomy case

Anatomical knowledge test

Fill in your number here

Pronation osteotomy

The questions in this anatomical test are regarding pronation osteotomy where the ulna and the radius are pronated. It is important to know that these questions are based on the clinical formulation (not anatomical) of pro- and supination, being that 0° pronation and 0° supination (neutral position) corresponds to the position of the forearm when smashing a fist in a table.

1. Give an example of an activity the patient was **not** able to do preoperatively but is able to do postoperatively (after being fully recovered from the surgery).
   - ☐ Cutting vegetables
   - ☐ Holding a dinner tray with one hand
   - ☐ Receiving change after payment
   - ☐ Screwing in lightbulb
   - ☐ Typing
   - ☐ Writing
   - ☐ Picking up a small object from a table
   - ☐ Closing zipper from pants

2. Give <u>two</u> examples of an activity the patient **was** able to do preoperatively but is **not** able to do postoperatively (after being fully recovered from the surgery). <u>Explain why.</u>

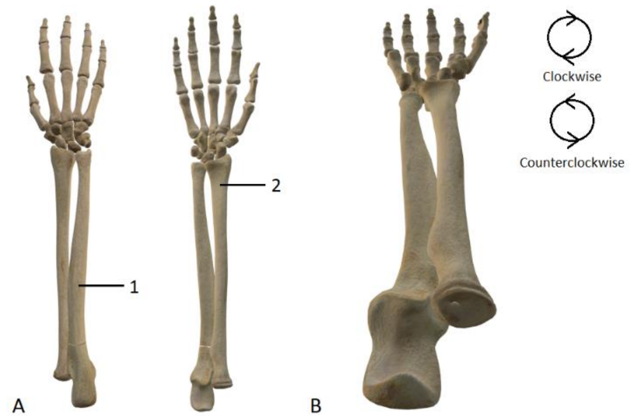
   1)____
   ____
   ____

   2)____
   ____
   ____

3. In the case that an osteotomy alone is insufficient because of active insufficiency, which of the muscles mentioned could be transferred in order to gain the desired result (pronation)?
   - ☐ Brachioradialis muscle
   - ☐ Biceps brachii muscle
   - ☐ Pronator quadratus muscle
   - ☐ Pronator teres muscle
   - ☐ Supinator muscle

4. a) Identify bone 1 and 2 in the figure below.
   1. ___________________________
   2. ___________________________

   b) Determine for both bones in figure B below with in which direction the distal part of the bone is rotated with respect to the proximal part during a pronation osteotomy.
   1. The distal part of bone 1 is rotated **[*clockwise / counter clockwise*]** with respect to its proximal part.
   2. The distal part of bone 2 is rotated **[*clockwise / counter clockwise*]** with respect to its proximal part.



Don't forget question 5 and 6 on the back of this paper!

5. A girl with a plexus brachialis injury has a range of motion of the forearm from 90° supination to 0° pronation. How many degrees should the forearm ideally be pronated during surgery?

   ______________ *degrees*

6. Both the radius and the ulna are pronated during osteotomy. Which bone should be pronated first, the radius or the ulna? <u>Explain why.</u>

   The ***[radius / ulna]*** *should be pronated first, because*_____________
   ____
   ____
   ____
   ____
   ____
   ____

D

Information Letter and Informed consent

D.1 | Information Letter (Dutch)

Proefpersoneninformatie voor deelname aan niet medisch-wetenschappelijk onderzoek

Het effect van 3D animaties op het begrip van veranderde functionele anatomie

Officiële titel: The effect of surgical animations on learning anatomy in medical education

Inleiding

Beste KT-student,

Met deze informatiebrief willen ik je vragen of je mee wilt doen aan een niet-medisch wetenschappelijk onderzoek. Deelname is geheel vrijwillig. Hieronder kan je lezen om wat voor onderzoek het gaat, wat het voor jou betekent, en wat de voordelen en nadelen zijn. Wil je deze informatie doorlezen, en beslissen of je mee wilt doen? Indien je mee wilt doen, kan je het informed consent formulier invullen.

Naast de informatie uit deze brief is het natuurlijk ook mogelijk om vragen te stellen aan de onderzoeker. Indien je liever met een onafhankelijk deskundige praat, raden we je aan om contact op te nemen met Katja Bogomolova. Zij heeft veel ervaring met dit soort onderzoeken, maar is zelf niet bij dit onderzoek betrokken.

Waarom vragen we je om mee te doen aan dit onderzoek?
Als eerstejaars KT-student leer je onder andere de anatomie van het menselijk lichaam. Voor het leren van de anatomie worden verschillende methoden gebruikt (zoals de snijzaal of een anatomische atlas). Wij nodigen je uit voor dit onderzoek, om de mogelijkheden te onderzoeken die de Microsoft HoloLens (augmented reality) kan bieden voor het leren van de anatomie.

Om wat voor onderzoek gaat het?
Dit onderzoek heeft als doel om na te gaan of studenten na het zien van een 3D animatie op de Microsoft HoloLens, de veranderde functionele anatomie beter begrijpen. We onderzoeken de volgende zaken:

- Zorgt het zien van een animatie van een operatie ervoor dat de veranderde functionele anatomie beter begrepen wordt?
- Is er een correlatie tussen het effect van de animatie en het spatiele vermogen van de student?

Wat betekent het voor jou als je meedoet?
Hoe lang duurt het onderzoek?
Het onderzoek bestaat uit één sessie en duurt in totaal ongeveer 1,5 uur.

Stap 1: ben je geschikt om mee te doen?
Je bent van harte uitgenodigd om mee te doen aan dit onderzoek zolang je in je eerste jaar van de studie klinische technologie zit. Je kan helaas niet meedoen als je al een andere studie of een ander vak hebt gevolgd waarbij de anatomie van het spierskeletsysteem uitgebreid wordt behandeld.

Stap 2: *3D inzicht*
Indien je besluit om mee te doen met dit onderzoek, vragen we je eerst een testje van 10 minuten op papier te doen. Deze test is bedoeld om je 3D inzicht in kaart te brengen.

Stap 3: *anatomische leersessie*
Je zal tijdens deze stap een patiënten casus krijgen. Daarbij worden instructies en leerdoelen gegeven om te bestuderen, hier krijg je 15 minuten de tijd voor. De anatomie in kwestie wordt bestudeerd op de Microsoft HoloLens (een augmented reality bril). Met augmented reality kan je in tegenstelling tot virtual reality wel je eigen omgeving zien. Dit heeft als voordeel dat de kans zeer klein is dat je je niet lekker zal voelen door het gebruik van deze bril. Afhankelijk van in welke groep je wordt ingedeeld krijg je 2 of 3 modellen te zien: het pathologische (preoperatieve) model, een animatie van de operatie en het postoperatieve resultaat. Er zullen twee casus behandeld worden, bij een van deze casus krijg je de animatie wel te zien en tijdens de andere casus niet.

D.2 | Informed Consent (Dutch)

Toestemmingsformulier

Ik heb de informatie voor de proefpersoon gelezen. Ik heb de mogelijkheid gehad om aanvullende vragen te stellen en heb daar een helder antwoord op gekregen. Ik had genoeg tijd om te beslissen of ik meedoe.

Ik weet dat mijn deelname geheel vrijwillig is. Ik kan op ieder moment beslissen om niet mee te doen zonder opgave van reden.

Ik weet dat mijn deelname geen invloed heeft op mijn studievoortgang en/of beoordeling op de (onderzoeks)afdeling.

Ik geef toestemming om mijn gegevens te gebruiken, voor de doelen die in de informatiebrief staan.

Ik weet dat alleen de onderzoeker mijn gegevens kan inzien. Haar/zijn naam staat vermeld in de informatiebrief.

Ik geef toestemming om gegevens nog 5 jaar na afloop van dit onderzoek te bewaren voor eventueel nadere analyse.

Ik ga akkoord met mijn deelname aan dit onderzoek.

Naam student:

Studentennummer:

Email adres:

Handtekening: Datum : __ / __ / __

Ik verklaar hierbij dat ik deze proefpersoon voldoende heb geïnformeerd over het genoemde onderzoek.

Als er tijdens het onderzoek informatie bekend wordt die de toestemming van de proefpersoon zou kunnen beïnvloeden, dan breng ik hem/haar daarvan tijdig op de hoogte.

Naam onderzoeker:

Handtekening: Datum: __ / __ / __

E

Normal Quantile-Quantile Plots

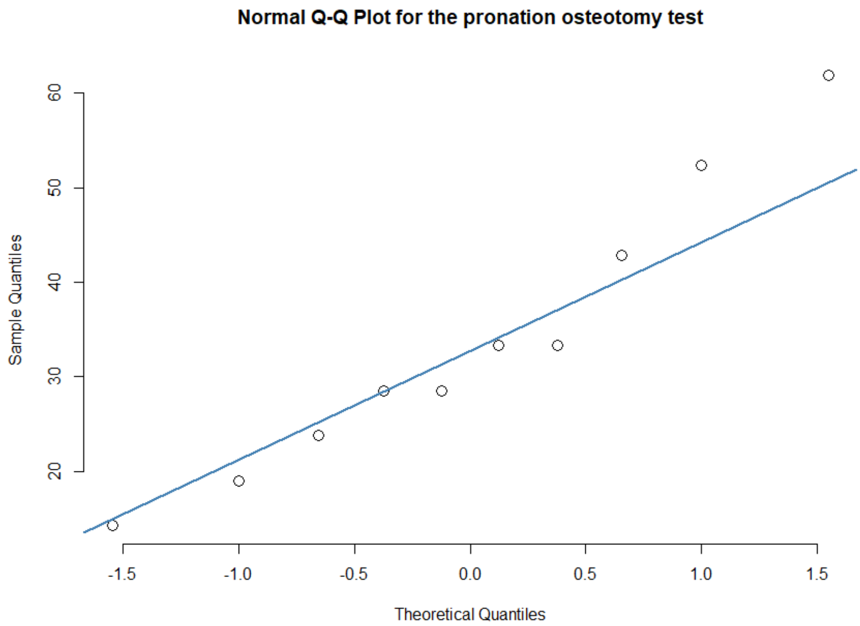


Figure E.1: Normal Q-Q plots for the pronation osteotomy anatomical test scores.

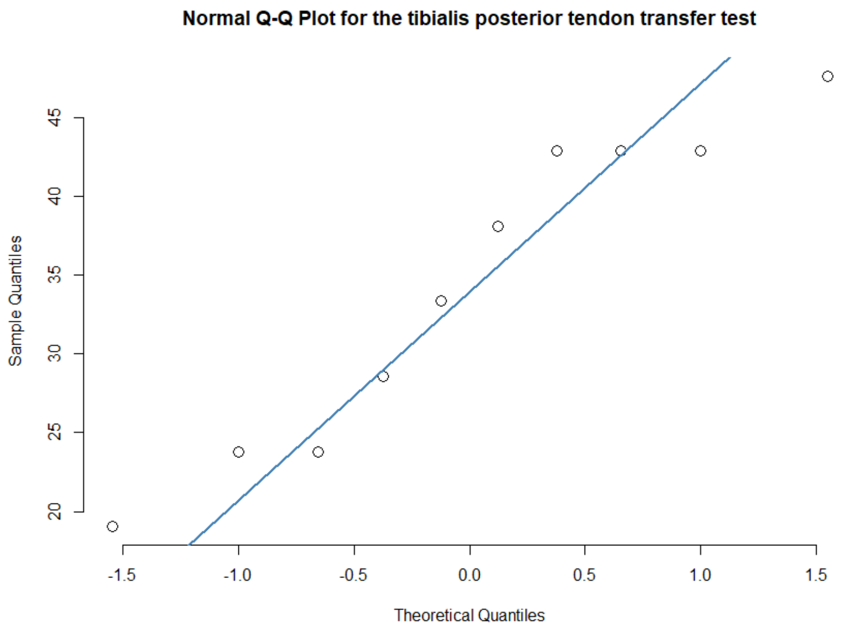


Figure E.2: Normal Q-Q plots for the tibialis posterior tendon transfer anatomical test scores.

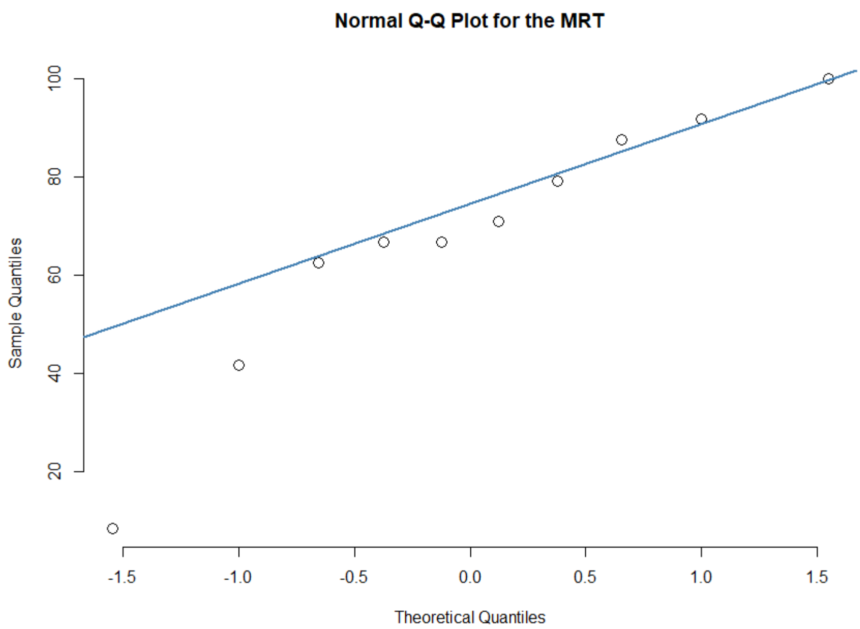


Figure E.3: Normal Q-Q plots for the MRT scores.

F

Lower Extremity Surgical Animation

In addition to previous attempts, a new endeavor was made to export the animation simulating a tibialis posterior tendon transfer using the lower extremity model.

Problem statement

The curve modifier that is used in this animation to pull the tibialis posterior tendon out of incision 2 and into incision 3 causes problems after exporting. If this animation is imported in Unity, it is not shown correctly. This is described more thouroughly in reports of previous internships (not published).

Up to now, the best method remains making an FBX-export of every keyframe. However, this takes up a lot of data as for every frame another object is shown instead of another location, rotation, scale or shape.

Current attempts

During the current attempt, this problem could not be solved. The origin of the tendon is aligned with the curve, which is necessary for it to follow the path with the right curve. However, while the object is following this path because of the curve modifier, the origin of the object moves straight over the x-axis. Based on the origin compared to the beginning of the curve, the object moves in a complete different direction over the path. Therefore, changing the place of the origin or keeping it static is not an option.

Moreover, this movement is not correctly captured in shape keys during a `.mdd`-export, which is why an `.mdd`-export alone is not successful for this case. This is the case both before and after deleting the curve modifier.

Another attempt that was explored, was only making FBX-exports for the objects and frames that were actually using the curve modifier instead of for all moving objects and all frames. In doing so, the amount of objects exported and thus the total amount of data could be highly reduced from 21 objects per frame to either 0 or 2 objects per frame. The remaining objects could be exported with a normal FBX-export. However, in Unity, this still gave problems because of the speed the animation is shown in (fps). This is differs depending on the processing load. Therefore the two different animations could not always be played at the same time yet.

Recommendations for future work

The recommended method to proceed is setting the frame rate of the animation and stop-motion in Unity to a fixed speed. Then, the two can be played at the same time and a new object will only be loaded for those objects containing a curve modifier. In this manner, the file size can be reduced from 7.45 MB to 3.97 MB. Then, every frame can be used instead of every fifth frame, and the stop-motion would not seem different from an animation to the human eye.

An alternative without using stop-motion all together would be to create an armature on the tendon in Blender with small bones such that the tendon can be moved freely. However, animating the movement of the tendon in this manner asks for a lot of precision and is extremely time-consuming and is therefore not recommended.

G

Object Name Export Script (Python)

```python
# import the necessary modules: blender's python API and python's os module
import bpy, os

# get the current selection
selection = bpy.context.selected_objects

# initialize a blank result variable
result = ""

# iterate through the selected objects
for sel in selection:
    # get collection to which the object belongs
    col = sel.users_collection[-1].name
    # write the selected object's name and dimensions to a string
    result += "%s, %s\n" % (sel.name, col)

# get path to render output (usually /tmp\)
tempFolder = os.path.abspath (bpy.context.scene.render.filepath)
# make a filename
filename = os.path.join (tempFolder, "newfile.txt")
# confirm path exists
os.makedirs(os.path.dirname(filename), exist_ok=True)
# open a file to write to
file = open(filename, "w")
# write the data to file and close it
file.write(result)
file.close()
```

H

Example rotation represented by Euler angles and Quaternions

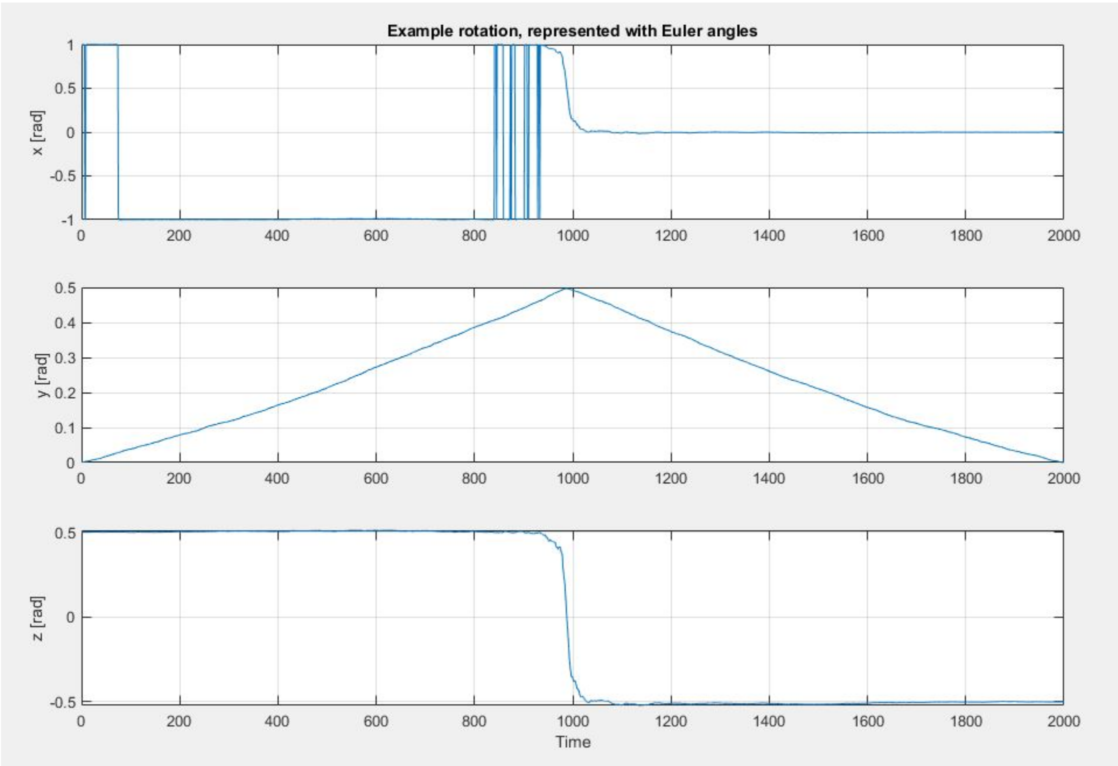


Figure H.1: An example rotation, represented with Euler angles, showing wrap around.

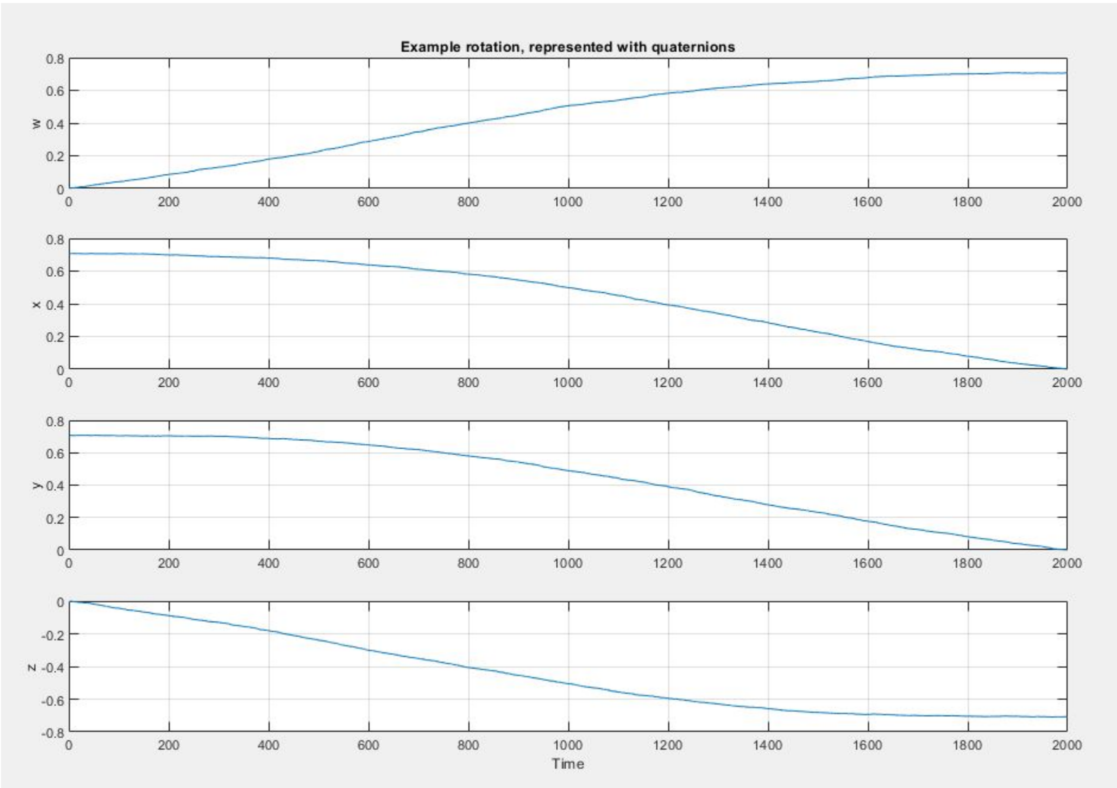


Figure H.2: An example rotation, represented with quaternions

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