Develeopment of Analysis Techniques for dynamic magnetic resonance imaging

– Master Thesis –

to be awarded

Master of Science in Medical Photonics

submitted by

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Abstract

Short summary of your thesis (max. 250 words) ...

Acknowledgements

If you want to thank anyone (optional) . . .

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FSU Jena	Friedrich-Schiller-Universität Jena

1 Introduction

1.1 The Knee

The knee, a pivotal structure in the human body, plays an essential role in locomotion. Additionally, it functions to control the center of body mass and posture in the activities of daily living by facilitating a wide range of movements. As such, the knee's health and integrity are vital for overall quality of life, influencing everything from basic mobility to participation in complex sports. In a comprehensive survey across 15 European countries and Israel, it was found that knee pain was the third most commonly reported location of chronic pain, highlighting the significant concern it poses to public health (Breivik et al. 2006). Furthermore, arthritis/osteoarthritis (OA) was identified as the most common cause of this pain.

And this situation has not improved with time. In Germany for instance, a recent retrospective study has found that the number of patients with OA is steadily rising (Obermüller et al. 2024). Part of the reason knee-related issues are so prevalent and impactful is the inherent complexity of the knee joint itself. As a hub of various anatomical structures working in unison, the knee supports a range of movements and bears significant loads, making it susceptible to a variety of injuries and conditions. Understanding the anatomy of the knee is the first step in tackling this problem.

Anatomy and Function

The knee joint is the largest and the most superficial synovial joint in the body. (Dalley, Agur, and Moore 2023). It comprises three primary articulations:two femorotibial articulations (see Figure 1) and one femoropatellar articulation. These articulations, illustrated in figures 1 and 2, are defined by their complexity and incongruence, features that are crucial for the joint's biomechanical performance.

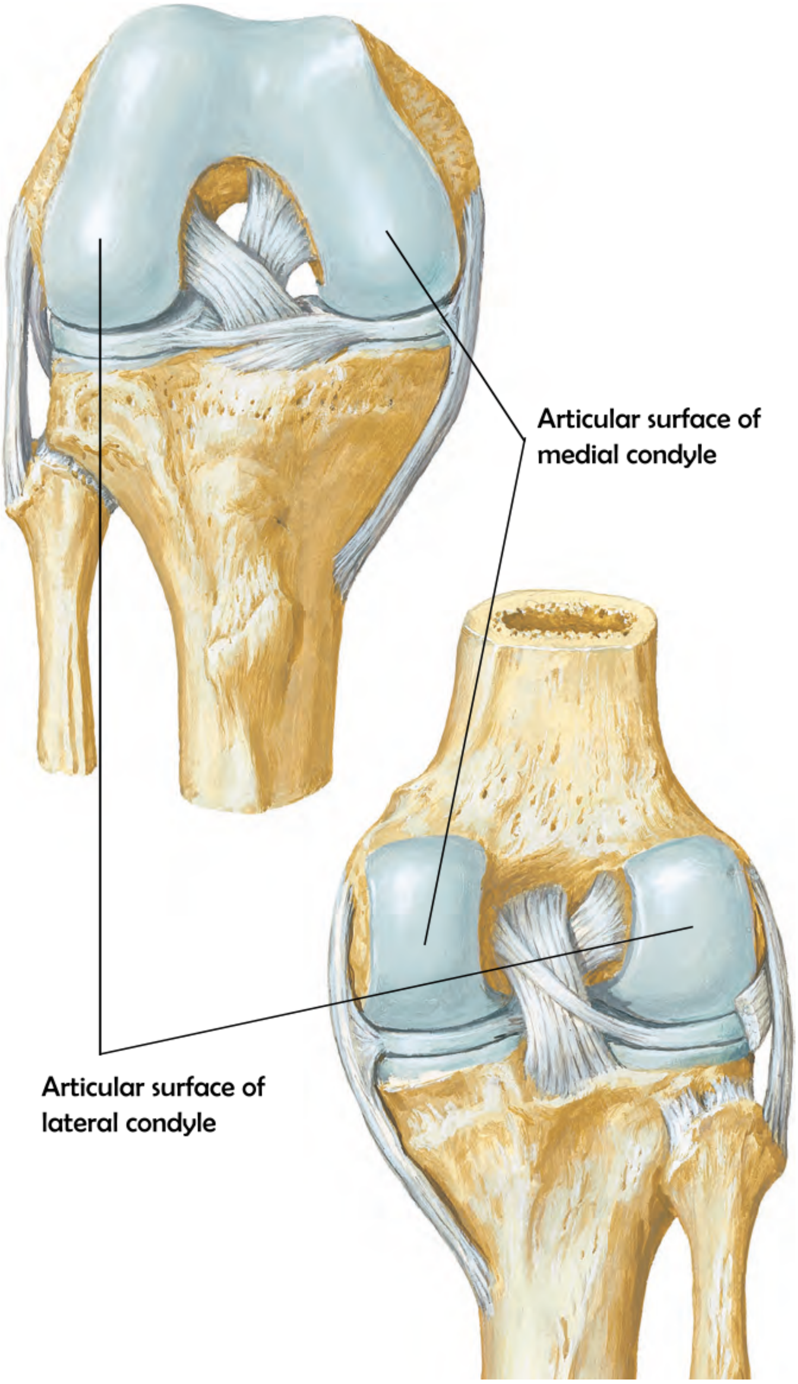

Figure 1: Anterior (flexed,top) and posterior (extended, bottom) view of the right knee with their articular surfaces labeled. (Netter 2023, p.519)

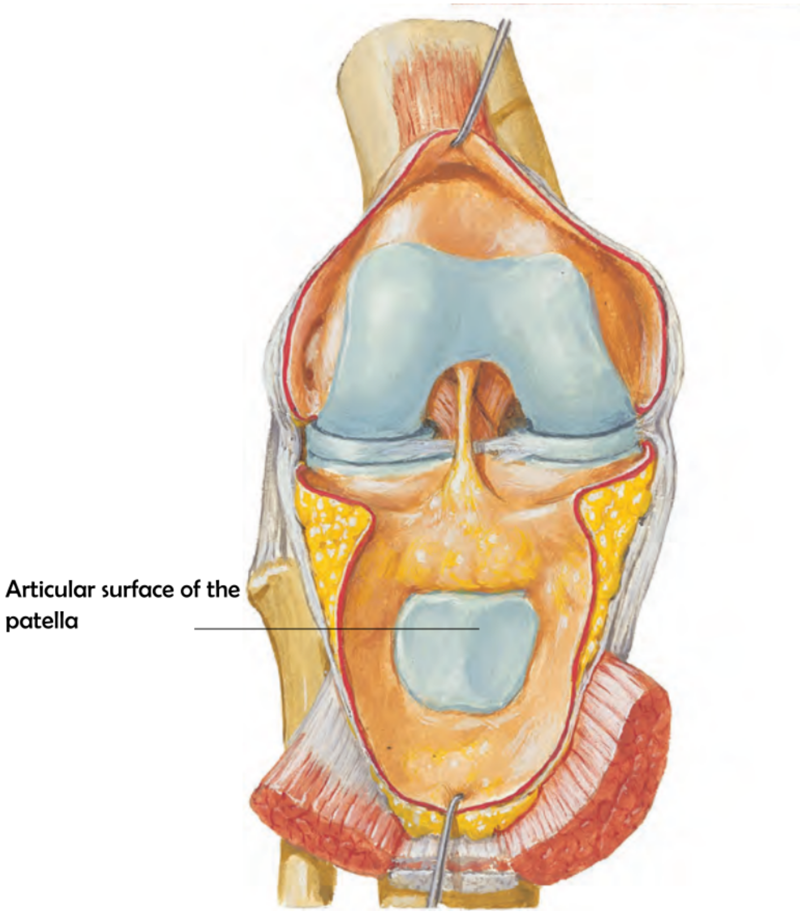

Figure 2: Right joint opened, knee slightly in flexion, with the patellar articulation labelled. (Netter 2023, p.517)

This design allows the knee to manage a wide array of movements and bear significant loads. Figure 3 illustrates the knee's capacity for multidimensional movement, highlighting the joint's sophisticated structural design that enables this versatility. However, this inherent design also renders the knee vulnerable to a range of forces (Standring and Gray 2021).

Such mechanical forces, influenced by activities and body mass index (BMI), are significant causes of OA and represent one of the most modifiable risk factors (Heidari 2011). Furthermore, abnormal joint loading is considered a key mechanical driver of osteochondral changes thought to contribute to the initiation and progression of knee OA (Coburn et al. 2023).

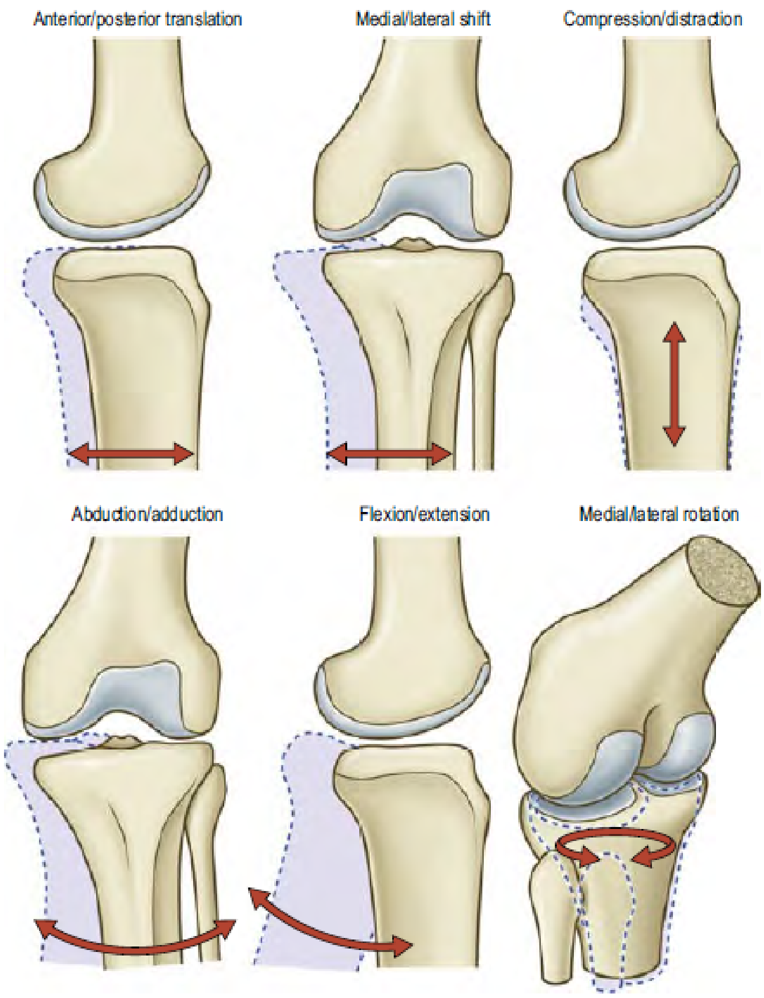

Figure 3: The knee joint motion in three dimensions, described using six independent variables (degrees of freedom) (Standring and Gray 2021, p. 1412).

The relationship between biomechanical stresses and knee health highlights the need for diagnostic tools that fulfill two key criteria: they must capture the knee's dynamic behavior during motion and assess the joint under varying loads. Dynamic magnetic resonance imaging (MRI) excels in meeting these requirements as one of the most advanced imaging modalities.

1.2 Dynamic MRI

In a broad sense, dynamic MRI is an umbrella term encompassing various MRI techniques designed to capture and visualize physiological processes and motion over time. This dynamic aspect of MRI is crucial when studying systems or structures where motion is inherent, such as blood flow, tissue perfusion, or cardiac movement. For the purposes of this project, the focus of ”dynamic MRI” narrows down to capturing the bulk movement of the knee joint undergoing active flexion extension cycles inside the scanner. Compared to traditional static MRI scans, which are highly susceptible to motion artifacts compared to other imaging modalities (Zaitsev, Maclaren, and Herbst 2015), dynamic MRI techniques not only accommodates motion, but can even leverage it to offer comprehensive insights into the functional and biomechanical properties of the concerned structures. Among these techniques, CINE imaging, particularly renowned in cardiac MRI, is considered the gold standard for evaluating cardiac function (Menchón-Lara et al. 2019). This high regard in cardiac MRI illustrates the method's precision and adaptability, traits we leverage for knee imaging.

CINE imaging

CINE is derived from the word cinematography, to create a movie. In the context of dynamic knee MRI, this technique can be used to reconstruct a ”movie” of a single flexion-extension cylce. This visualization is achieved by aggregating multiple partial datasets acquired over various cycles. The knee's movement cycle is segmented into distinct stages, each corresponding to a specific angle of flexion or extension. For each stage, k-space — the Fourier transform space from which MR images are reconstructed — is incrementally sampled. This data is gathered across multiple repetitions of the movement cycle, ensuring comprehensive coverage of k-space and thus, high-resolution imaging of each movement phase.This technique works robustly only if the cycles are sufficiently similar (Curtis and Cheng 2022).

To further address the challenge of motion artifacts and to maximize the potential for precise image reconstruction, a previously reported radial golden-angle gradient-echo FLASH sequence was used, which is more robust against motion artifacts than Cartesian sequences (Aleksiev et al. 2022). The following sections will detail the key components of this technique — radial golden-angle acquisition and the gradient-echo FLASH sequence.

Radial golden-angle acquisition

As the name suggests, radial golden-angle acquisition specifically modifies how k-space is sampled. Unlike traditional static MRI, which typically employs Cartesian sampling, this method utilizes radial sampling. Here, the data points are collected along radial lines spreading out from the center of k-space, resembling spokes on a wheel. Figure 4 depicts a generic radial sampling scheme. The separation between

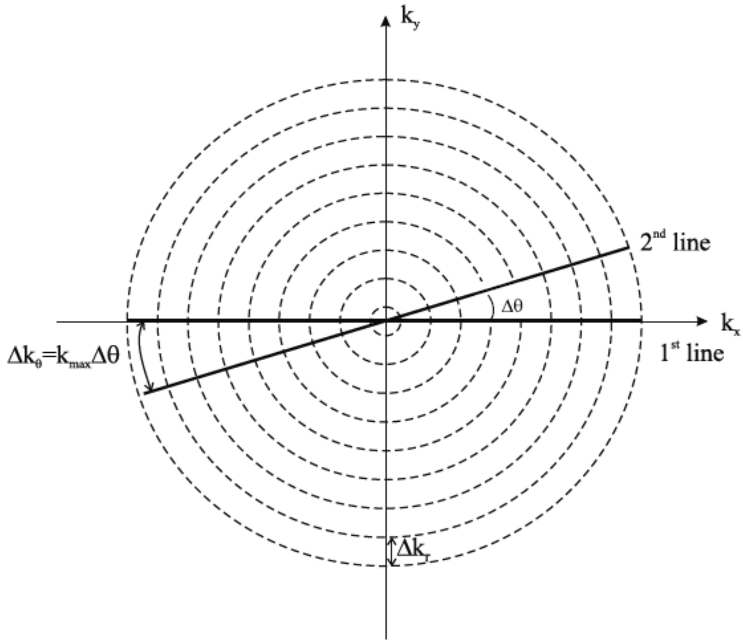

Figure 4: Generic radial k-space sampling (Brown et al. 2014, p.306)

any two adjacent circles defines the separation Δk_r in the radial sampling direction, whereas, the angular separation between any two successive angular lines in k-space (such as between the two example lines shown in the figure) defines $\Delta\theta$. The two quantities Δk_r and $\Delta\theta$ are constrained by the Nyquist sampling criterion. (Brown et al. 2014)

The 'golden-angle' strategy, which we employ, optimizes this approach by spacing the radial lines at an angle of approximately 111.25 degrees. This specific angle helps in evenly covering the k-space without overlapping, ensuring that each new image frame provides unique information, thus enhancing image quality and temporal resolution.

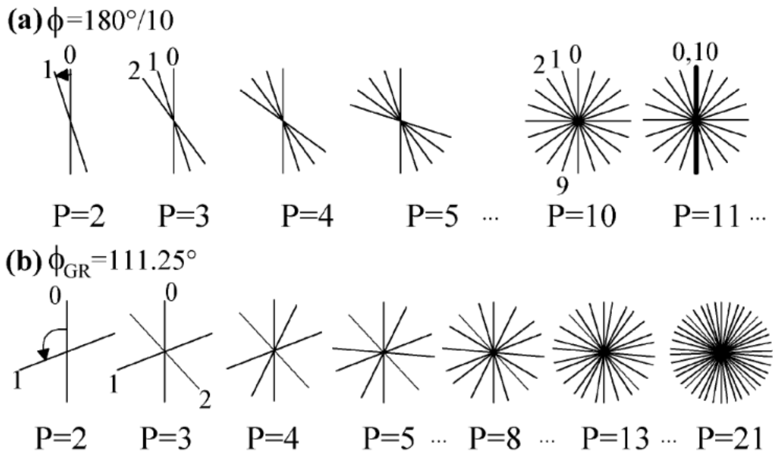

Figure 5: Radial k-space sampling strategies. (a) Fixed angular increment, showing potential for uneven k-space coverage. (b) Golden-angle sampling, ensuring uniform distribution across k-space (Winkelmann et al. 2007).

Figure 5 provides a visual comparison between traditional fixed increment and the golden-angle methods in k-space sampling. It highlights how each approach affects the distribution of sampling lines across k-space. In the figure, part (a) shows radial sampling using a fixed angular increment. This traditional method can lead to gaps or overlaps in data collection, depending on the number of radial profiles used. Part (b) demonstrates the golden-angle method, where each new radial line is placed at an increment of approximately 111.25 degrees. This approach allows for a more uniform distribution of sampling lines across the k-space, enhancing image quality by preventing gaps and reducing redundancy in data collection. Figure blank shows the k-space of a specific frame during the knee flexion cycle and the corresponding reconstructed MRI image.

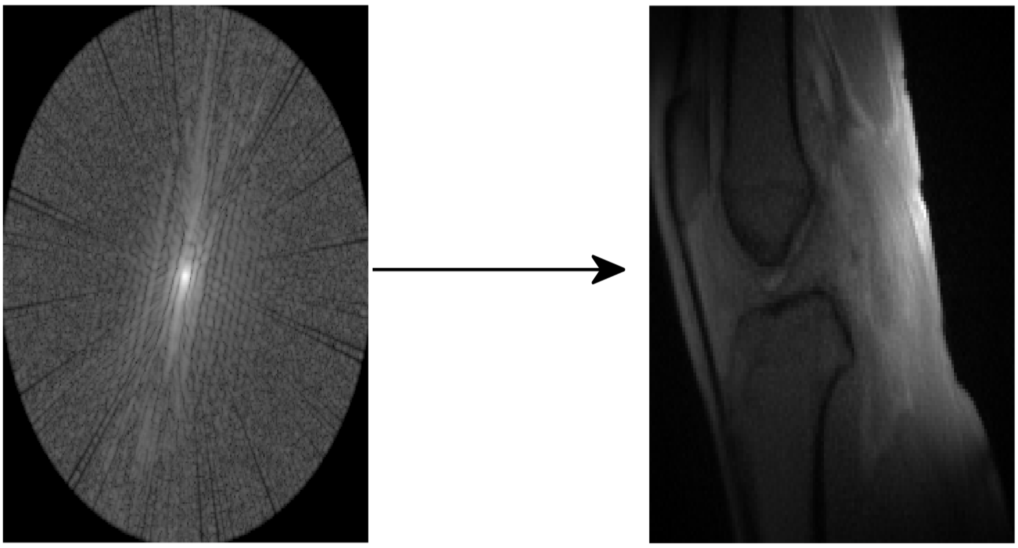

Figure 6: **Example of k-space and reconstructed image**. Left: K-space data from a specific angle during the knee flexion cycle. Right: Corresponding reconstructed MRI image, illustrating the detailed visualization achievable through golden-angle sampling.

Gradient Echo FLASH sequence

High resolution CINE imaging

This imaging technique presents a significant advancement in capturing active knee motion. It combines **continuously acquired radial golden-angle MRI** data with angular sensor information to **retrospectively reconstruct** CINE images of the knee, allowing the acquisition of high-resolution 2D images during knee flexion and extension.

Gating

Gating is a technique used to synchronize image acquisition with a repetitive physiological motion, such as heartbeats in cardiac MRI or joint movements in musculoskeletal MRI. In the context of dynamic knee MRI, gating ensures that the images captured at different times correspond to the same stage of the knee's motion cycle

Knee loading device (Brisson et al. 2022)

1.3 Research Necessity

Discuss the necessity for further analysis of the acquired images, emphasizing the gap between data collection and data interpretation within the current literature.

Clearly state the objectives of your research, focusing on the development of new analytical techniques to interpret the existing dynamic MRI data.

Explain the expected contributions of your research to the field, including the potential implications for biomechanical understanding and clinical applications.

1.4 Thesis Structure

Structure of the thesis is as follows:

2 Methodology

some text

2.1 Data Collection Methods

2.1.1 The Device

A novel MRI-compatible device was integrated into the MRI scanner setup to facilitate guided knee motion in patients (Brisson et al. 2022). This device allowed for a range of motion of approximately 30 degrees, enabling subjects to perform knee flexion and extension cycles under both loaded and unloaded conditions. For loading, the device was equipped with compartments for weight plates (maybe picture here?) and sandbags, providing a physiological load of 10 to 12 kilograms.

Central to this device's functionality is an optical fiber position sensor actual citation needed?(MR3 Y10C10, Micronor, 155 Camarillo, CA, USA), which precisely which measures the ab solute angle from 0° to 360° with a resolution of 0.025°. This measurement capability is critical for synchronizing the knee's movement with MRI data reconstruction. To enhance signal acquisition and the clarity of imaging, two flexible coils (cite the coils here, perhaps also show a picture) were positioned at key anatomical locations: one at the distal femur and another at the proximal tibia, as specified in the MRI protocol. perhaps show a picture outside the scanner of the patient wearing it?

2.1.2 Procedure Details

MRI measurements were performed on four healthy volunteers (aged between 28 and 37 years, body mass between 55 and 90 kg) using a clinical 3 T Siemens Prisma fit scanner. Volunteers had no known musculoskeletal conditions and gave written informed consent in accordance with the guidelines set out by the institutional ethics committee. from device paper For all of these subjects, the left leg was used.

The thigh is secured on a wedge positioner, and the lower leg is attached to an ankle rest, just above the malleoli, using Velcro straps to minimize lateral movement. Once positioned at the scanner's isocenter, the volunteer then engages in a controlled exercise, following a metronome set at 60 beats per minute. This pace dictates a four-beat flexion to extension cycle, where the leg is flexed at the first beat and fully extended by the fourth. This exercise is performed for approximately 2 minutes throughout the duration of the scan, totaling between 100 to 120 repetitions. Initially conducted under a loaded condition with weights, the process is repeated without the added resistance to compare both states.

2.1.3 Sequence Parameters and Reconstruction

2.2 Data Analysis

All the analysis and data visualization were done using the python programming language (v3.11.5). To begin, the data in nifti (Neuroimaging Informatics Technology Initiative) format is loaded using nibabel (v5.1.0) library. It is then visualized using napari(v0.4.18), a multi-dimensional interactive image viewer in Python.

2.2.1 Segmentation

Step 1: Edge Detection Using the Canny Algorithm

The Canny filter (Canny 1986), as implemented in the scikit-image's feature library (v0.21.0), was employed to apply an edge filter to the images. Various parameters of the Canny algorithm were adjusted, including edge thresholds and Gaussian blur, to optimize edge detection. Subsequently, the scikit-image's morphology library was utilized to remove small elements from the binary image. The image was then skeletonized to a one-pixel width, retaining only long and consistent edges. The final selection of the desired edge was accomplished using scipy's label algorithm (v1.11.3).

2.3 Validity and Reliability

Validation Methods: Detail the steps taken to validate the segmentation techniques and the biomechanical parameters you derived. Reliability Measures: Describe any repeat analyses or cross-verifications done to ensure the consistency and reliability of your results.

3 Results

3.1 Segmentation

some text

3.2 Parameter Extraction

some text

4 Discussion

4.1 Technique Evaluation

Assess the effectiveness and accuracy of your segmentation techniques.

4.2 Biomechanical Insights

Discuss the biomechanical parameters obtained and their implications for understanding knee movement.

4.3 Comparison with Existing Methods

Compare your results with current analysis techniques.

5 Conclusion

5.1 Summary of Contributions

Recap the novel analysis techniques developed and their significance.

5.2 Limitations and Challenges

Discuss any limitations encountered and the challenges in the analysis process

5.3 Future Work

Suggest potential improvements and future directions for research

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A Appendix

If needed for supplementary material, such as detailed description of data collection, tables, or figures.

Statutory Declaration:

I declare that I have developed and written the enclosed Master Thesis completely by myself, and have not used sources or means without declaration in the text. Any thoughts from others or literal quotations are clearly marked. The Master Thesis was not used in the same or in a similar version to achieve an academic grading or is being published elsewhere.

Place, Date

Signature