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## The biomechanical outcome after total hip replacement

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## State of the Art

### Total Hip Replacement

HIP arthritis, also called Coxarthrosis or Osteoarthritis (OA) in general, has been a disease pattern for centuries<sup>1</sup>. Archaeology has provided us with evidence for joint pathologies in many different populations ranging from early Neanderthal populations<sup>2</sup> to relatively modern homo sapiens populations (Saxons, medieval<sup>3</sup> or Roman<sup>4</sup>). Due the lack of proper surgical techniques, proper implants or the hygiene in the operation room the treatment of such a disease was basically amputation for thousands of years. Only after the understanding of the human body as a musculoskeletal and biomechanical system increased, the first surgeons in the 18<sup>th</sup> and 19<sup>th</sup> century were ready and prepared to perform such interventions<sup>5</sup>. Whilst there were spectacular successes, the outcome of such an operation was practically unpredictable; the chances for improvement of the patients were low. In 1821 the first excision of a hip joint was performed by a surgeon called Anthony White (1782-1849). He did not report the operation himself, but this operation gained him recognition in the medical/scientific community. He was able to reduce pain and to preserve mobility, but only for the sake of stability. The first synthetic mold prostheses have been implanted in 1923 by a Norwegian born, American surgeon called Marius Smith-Petersen. He also developed the anterior surgical approach that still bears his name<sup>6</sup>. In the 1940s Robert Girdlestone popularized the resection of the femoral head. His radical excision arthroplasty bears his name and is still used as last resort in failed THR, euphemistically called 'conversion to Girdlestone'<sup>7</sup>. The first hip arthroplasty products that were widely distributed have first been developed by the Judet brothers<sup>8</sup> and have been refined of the following decades by many others to a point where the implant even allowed bone ingrowth<sup>9-11</sup>. Peter Ring used cementless components with a metal-on-metal articulation in 1964. With his technique he was able to achieve a survival rate of 97% after 17years<sup>12</sup>. His model was abandoned in the 1970s in favor for the Charnley model, but was 'rediscovered' in the 1980s. Nevertheless, the stage was set for the evolution of a truly successful procedure that is named after its inventor, Sir John Charnley<sup>13</sup>. Today Hip Replacement (THR) is one of the most performed orthopedic interventions and because of the demographic change that our society is subject to, the number of operations is likely to further increase<sup>14,15</sup>. The main goal of THR is to restore

the patients well-being and function so that he or she is able to participate in normal life without persistent pain or restrictions in activities of daily living (ADL).

In order to improve the intervention and shorten hospitals stays minimally-invasive surgery (MIS) has been developed. Over the past decade MIS-THR has been controversially discussed and it still is. Supporter of MIS-THR claim that the benefits of MIS-THR are less blood-loss, less tissue trauma and earlier recovery of the patients<sup>16–18</sup>. Critics of MIS-THR argue that the poor visibility during MIS leads to poor implant positioning<sup>19–21</sup>. Also the improvement of the early outcome has been doubted by some authors<sup>22,23</sup>. Whilst some of the above mentioned studies discuss some correct arguments, meta-analysis of the scientific literature disproves most of the points mentioned<sup>24–26</sup>. Proper Implant positioning can be achieved due to the use of a computer-assisted System (CAS)<sup>27</sup>. Systems like this are often expensive and their application has to be justified by an improved postoperative outcome of the patient.

One of the major clinical challenges during Total Hip Replacement (THR) is to find an optimized compromise between the trias of hip biomechanics, tribology and postoperative functionality. In the end, all three elements are dependent on each other: The position of total hip components correlates to the risk for dislocation, implant failure, articular wear and prosthetic range of motion (ROM). It is a fact that sub-optimal implant component position and orientation with respect to each other leads to either bony or prosthetic impingement<sup>28,29</sup>. Sub-optimal implant orientation also leads to so called edge- or rim-loading which causes higher wear rates in the implant system, subsequently leading to a shorter lifespan of the implant system<sup>30</sup>. Early impingement occurs when contact between the prosthetic femoral neck, the acetabular cup and/or bony parts (e.g. greater trochanter, acetabular rim, resection plane) occurs within a patient's normal ROM. Several authors have proposed starting with the preparation of the femur and then transferring the patient-individual orientation of the stem relative to the cup intraoperatively ('Femur First'/'combined anteversion') in order to minimize the risk of impingement and dislocation (see Figure 1)<sup>31–33</sup>.

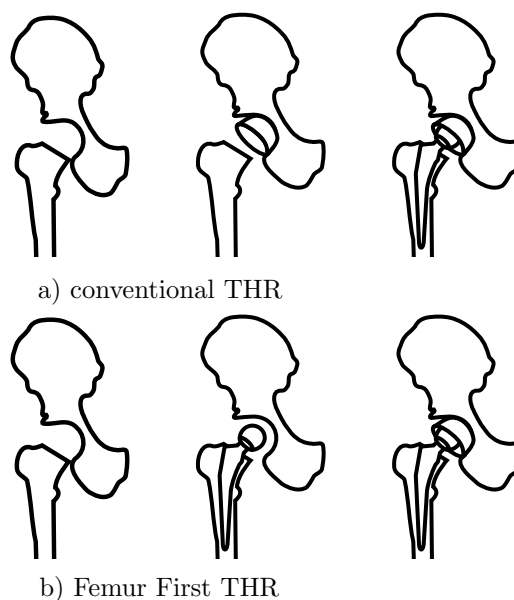


FIGURE 1: THR workflow; a) conventional THR workflow b) 'Femur First' workflow

To address this issue a novel, computer-assisted surgical method (CAS) for THR following the concept of 'Femur First/combined anteversion' (CAS FF) has been developed. This incorporates various aspects of performing a functional optimization of the prosthetic stem and cup position in order to improve implant component positioning and orientation<sup>34-36</sup>.

## Motion Capture Gait Analysis

As stated before, one of the main goals of modern THR is to restore the patients' ability to participate in normal life. One of the most performed ADL for THR patients is walking<sup>37</sup>. Over the time course of one day, people walk up to 15.000 *steps/day*. This sums up to about 2 – 5 *million steps/year* and to a mean distance of 27.000 *km/year*. Restriction in walking, or an 'unusual' way to walk may lead to an unfavorable load-case throughout the musculoskeletal system. Amongst others, OA is partially caused by 'wear and tear' which means that abnormal forces in particular areas of a joint may lead to OA<sup>38</sup>. Therefore an 'unusual' way to walk that causes abnormal load-cases in the musculoskeletal system is additionally to gender and age another risk factor that may promote Coxarthrosis even further. This raises the question, what is an 'unusual' way to walk? To analyze 'unusual' and 'usual' gait patterns, scientists use gait analysis. The term 'gait analysis' actually refers to different ways of analyzing walking in a controlled, laboratory environment. In general gait analysis consists of three pillars, where all three reflect different aspects of human walking (Figure 2).

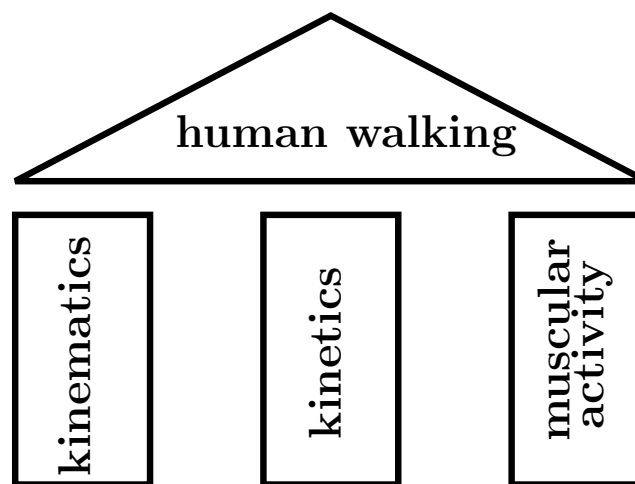


FIGURE 2: The three pillars of human gait

Kinematics refers to the gait pattern which is a combination of different joint angles over time in all three spatial dimensions. The range from minimum to maximum joint angle is the active range of motion (aROM) and a measure if one is restricted in walking. Because the motion itself can be carried out in more than one anatomical plane it requires active muscle activation. The aROM can be assessed due to visual estimation, two-arm goniometer and motion capture (MoCap) systems (see Figure 3). In order to determine the error of measurement many studies have been conducted<sup>39-41</sup>. The clinical use of gait analysis has been proven<sup>42</sup> as well as it has been previously used for investigating operation-dependent differences<sup>43-45</sup>.

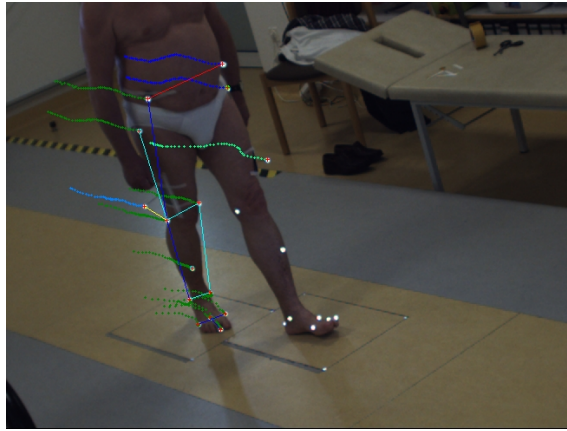


FIGURE 3: A snapshot of a video based gait analysis. The reflective markers are recorded over a certain time-span and result in marker trajectories. Such marker trajectories can then be used to reconstruct the gait pattern in 3D over time.

Kinetics refers to physical forces or moments in or outside the human body. One kinetic measurement are ground reaction force (grf) measurements during walking. It gives feedback of how much force (according to Newtons second law) the ground has to provide so the person is fully mechanically constrained. They have a very characteristic 'two peak' curve that give insight into the walking dynamics. Figure 4 displays ground reaction forces as measured during walking for the right and for the left leg. The distinct characteristics are highlighted with circles, they occur in different phases of gait. Characteristic 1 occurs when the foot is in full contact with the ground and the knee joint locks to be able to transfer the load throughout the body and facilitate locomotion<sup>42</sup>. Characteristic 2 (peak) occurs when the upper body is transferred over the leg which is in contact with the ground. Characteristic 3 (peak) occurs when the leg which is in contact with the ground pushes the body up from the ground. The peaks are usually around  $1.1 - 1.3 \times \text{bodyweight}$  but always higher than the body weight. Characteristic 4 (trough) occurs when the opposite leg swings and the center of mass of the whole body is transferred over the ground. The trough is usually around  $0.8 - 0.9 \times \text{bodyweight}$  but always lower than the body weight. By combining the gait pattern and the ground reaction forces it is possible to compute the joint moments using inverse dynamics<sup>42</sup>. The muscles of the human body produce this 'driving torque' for the body segments to facilitate locomotion. Even though this is an integral measurement for all muscles and that cannot be divided into single muscles, such joint moments are the only information that gait analysis can provide about the *in vivo* biomechanics.

The third pillar of gait analysis is muscular activity. The muscles of the human body are the force-producing elements that facilitate locomotion by providing the force needed to move a body segment. One of the challenges with muscle activity is that the actual force exerted by a muscle cannot be measured, only the electric current produced by the central nervous system (CNS) that is used to activate it the muscle activity. Muscle activation itself is already a complex phenomena therefore measuring it is also quite complex. The greatest challenge is to produce repeatable results. Measuring muscle activation is based on measuring the neural activation potential that is sent from the CNS to activate the basic motor control units. This can be done in an invasive way (needle electrodes) or in a non-invasive way (surface electrodes). Needle electrodes produce the

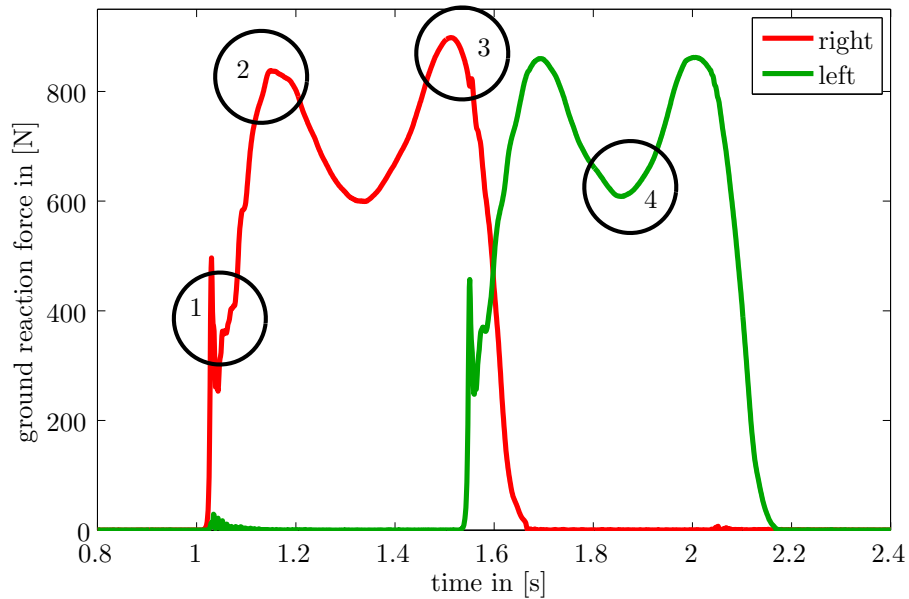


FIGURE 4: Ground reaction forces for the right and left leg during walking and the typical characteristic peaks

most accurate results, but since the technique is invasive, it is not advisable to be used in a greater collective. Surface electrodes can be used in greater collectives, but they are subject to several challenges. First is the proper placement of the electrodes. Even though this is standardized it is not always repeatable as well as it needs some skin preparation<sup>46</sup>. Second is the crosstalk by other muscles. Since the electrodes are placed on the skin, there is a high chance that the activation of a nearby muscle is also measured<sup>47</sup>.

## Biomechanical Modeling

Even if gait analysis can give important feedback when a gait pattern is pathological, its pitfall is that there is only little information about the internal biomechanics of the human body. The combination of gait pattern with ground reaction forces allows the computation of joint moments but other biomechanical like joint reaction forces (jrf) or single muscle forces cannot be computed. Those entities are especially important for implant design and function, for example if edge- or rim-loading occurs during various ADL. Depending on the region of interest, in this case the hip joint, the jrf may be called hip reaction force (hrf) meaning the force the hip joint has to provide to facilitate locomotion. In this context, the hrf with respect to the acetabular cup is a measure if critical hip joint loading occurs. They can be obtained by direct measurements or mathematical models. One way to measure the hrf is the use of instrumented implants<sup>48-50</sup>. Basically, instrumented implants are a load cell implanted in the human body. This technique is subject to several challenges. First the load cell system has to be small enough to fit into an implant, but still has to be strong enough to carry the load of the entire body. Second, the data acquisition has to be carried out wirelessly. Third, the system has to be maintenance-free, there is no margin of error since it is medically and ethically unacceptable to explant the implant, repair it

and implant it again. Once these challenges are overcome the technique of instrumented implants provides great insight into the biomechanics of the hip joint. Researching into greater patient numbers in the form of prospective randomized trials is however not possible using this method. Another approach to obtain hrf is using mathematical models. The first mathematical model has been developed by Pauwels et al. and it was ground-breaking not because of its accuracy but rather because of the drastic view on the human body as a mechanical system from a physicist and engineers point of view<sup>51</sup>. The first model (to the authors knowledge) to estimate the hip reaction forces during gait by means of a mathematical model was developed by Blumentritt et al.<sup>52</sup>. Even though his model drastically underestimates the hrf, it is the first to incorporate the dynamics of human gait. Because of the limited computational power at the time such models had to be analytically solvable, which is practically impossible for over-determined system such as the human body. Nowadays with the increase of computational power, new methods have been developed to solve those over-determined systems by the use of rigid-body models to a point where they even include the particular muscles and therefore muscle forces<sup>53,54</sup>. Models like this have to be validated, which is possible through a variety of ways not only through instrumented implants<sup>55,56</sup>. These models are called musculoskeletal models (MM) and they have already been used for the estimation of biomechanical outcome of THR<sup>30,57,58</sup>. Such model can be individualized to many aspects of human biomechanics. The patient-specific gait pattern can be used as input just like the patient-specific anatomy until reaching a highly detailed representation of the individual.

In this context researching ADL like walking and restriction of patients thereof is of special interest. The *AnyBodyModeling System*<sup>TM</sup> (AnyBody Technologies, Aalborg, Denmark) is a simulation environment that uses sophisticated models of the human body to compute the *in vivo* biomechanics during various ADL, such as gait. The jrf in combination with volume models of the region of interest and the respective muscle force can even be further used for e.g. individualized Finite Element Analysis (FEA - see Figure 5)

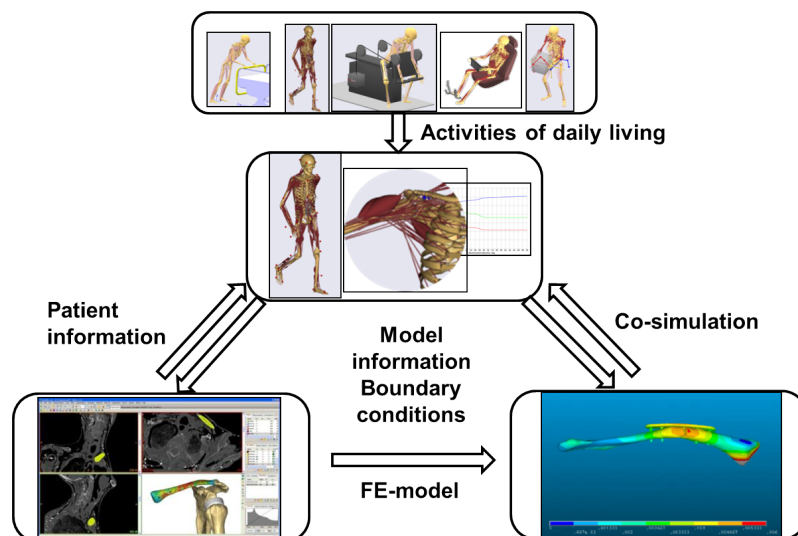
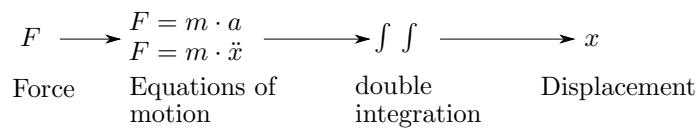


FIGURE 5: Patient-specific musculoskeletal modeling workflow including individualized FEA processing

This simulation environment is divided into the *AnyBody Managed Model Repository - AMMR* and the *AnyBodyModeling System*<sup>TM</sup> - *AMS*. The *AMMR* is a library of different models that

perform various ADL such as sitting, riding a bike or walking. It is publicly available and free for everyone to adapt the model to the specific question. The *AnyBodyModeling System* is the simulation environment that is capable of using the models of the AMMR. The computation of the *in vivo* biomechanics is based on the principle of 'inverse dynamics'. Inverse dynamics is a method that allows computing the force needed for a certain displacement of, for example, body segments. This is *vice versa* to forward dynamics, where the displacement is computed based on certain forces. Inverse dynamics is computationally beneficial while both methods lead to the same results<sup>59</sup>. Once it is determined what force is needed to create a certain displacement (motion), the over-determined system of equation is solved. For this a customizable optimization algorithm picks one solution that suits the best from the many. In a last step the user has to make sure that the applied optimization algorithm produces physiological reasonable results.

a) forward dynamics



b) inverse dynamics

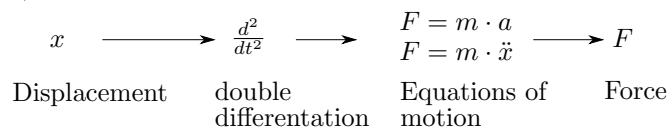


FIGURE 6: Mathematical description of a) forward dynamics b) inverse dynamics

A typical workflow how over-determined systems are solved and how a gait laboratory can be facilitated in this context is shown in Figure 7. First the kinematic boundary conditions (kinematic BC's), like movement that results from gait analysis, are defined as well as the joints and their type (spherical joint, revolute joint) are determined and modeled mathematically. Then the kinematic analysis solves the kinematic constraints. After that the position, velocity and acceleration of all segments (body parts) in the model are known. The kinetic boundary conditions (kinetic BC's) define the load transfer between the respective segments, as well as external forces (such as ground reaction forces during gait) are applied on the model. From the kinematic and kinetic information the over-determined and redundant system of equations is formed. An optimization algorithm (muscle recruitment scheme) finds a solution how the forces are distributed across joints and muscles throughout the system. Verifying and validating this optimization and if it produces physiological reasonable results is up to the user<sup>56</sup>. After a solution has been found the muscle and joint forces as well as interface forces are computed. Data retrieved from a gait lab delivers the necessary kinematic BC's, the imposed movement as well as external forces.



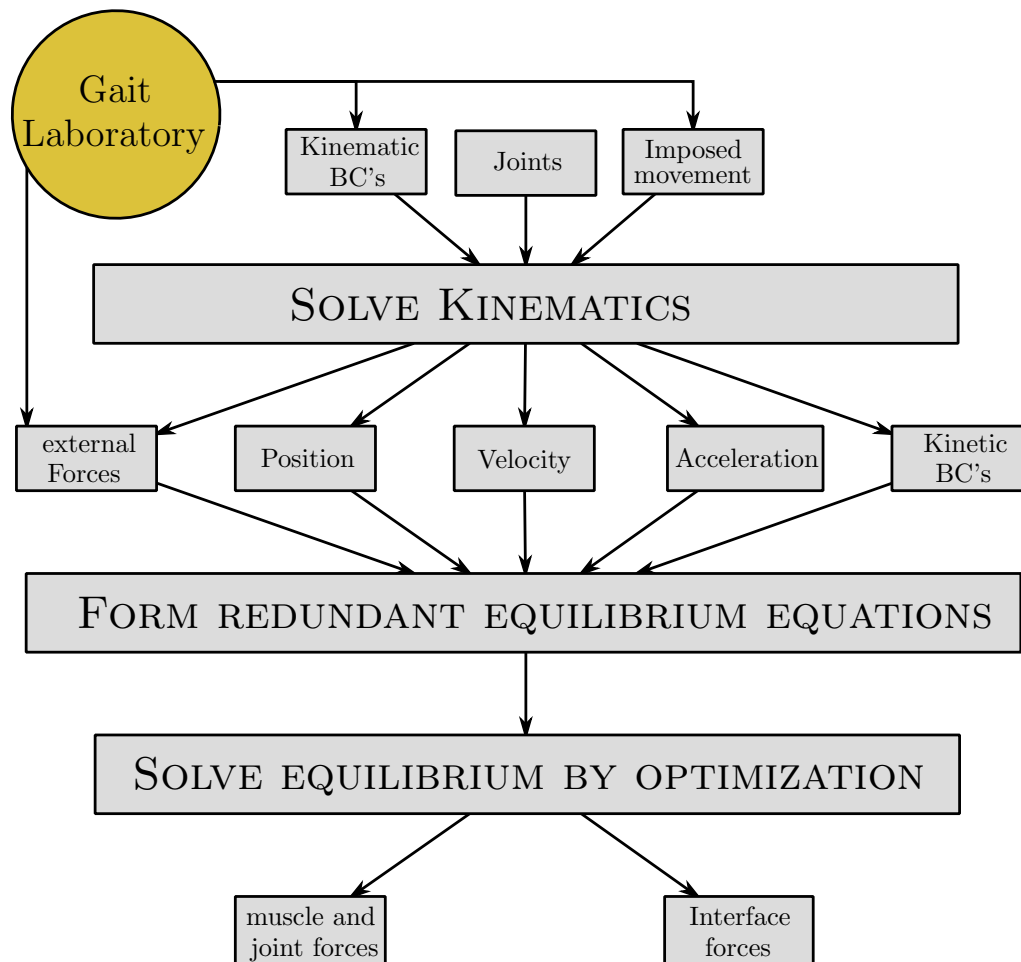


FIGURE 7: General Workflow for inverse dynamics computations including a gait laboratory

## Research question

It is the objective of this thesis to research the outcome of THR and especially the biomechanics of human walking after THR using patient-specific musculoskeletal models. First, different subjective and objective Outcome Measures (OMs) are systematically reviewed and recommendations on their use and scientific applicability are given. Second, it is the scope of this work to provide evidence that Minimally-Invasive Surgery is favorable compared to conventional surgery in terms of biomechanics. Third, it is the objective to compare two procedures for THR during a prospective, randomized and double blinded clinical trial (prct), where one of the techniques optimizes the implant component orientation with respect to each other following the concept of 'combined anteversion / femur first' and makes use of computer-assisted surgery (computer assisted femur first - CAS FF). Compared to MIS conventional THR, it is unknown if:

- i) CAS FF leads to an increases gait performance for patients postoperatively due to a greater unrestricted ROM
- ii) CAS FF leads to favorable musculoskeletal loading conditions at the hip joint due to an optimized implant orientation with respect to each other

## Outline

This thesis is divided into five sub-studies, all of them dealing with a different aspect to approach the research question. A systematic review of existing outcome measures to evaluate THR in a quantitative manner is performed in Chapter 2. The main goal of this chapter is to categorize existing Outcome Measures, to give an inventory on the use and scientific applicability of Outcome Measures and provide following scientists with recommendations for their use in daily practice. Chapter 3 investigates the influence of muscle trauma as caused by different surgical approaches for THR on the hip reaction forces during a bilateral squat by means of musculoskeletal models. Especially, it compares conventional surgical approaches with Minimally Invasive ones with the focus if MIS approaches are favorable from a biomechanics perspective. It is the goal of Chapter 7.2.1 to determine if computer assisted femur first (CAS FF) following the concept of combined anteversion/femur first is advantageous in terms of patient walking performance when compared to conventional (CON) THR. This is achieved using highly accurate Motion Capture (MoCap) gait analysis at three time-points (pre-op, post-op six months, post-op twelve months) during a prospective randomized controlled trial (prct). In Chapter 5, a novel method for quantifying the biomechanics during gait is presented. The proof-of-concept study introduces the concept of hip reaction force with respect to cup as computed by patient-specific musculoskeletal models in order to determine critical hip joint loading, as well as it proposes a method to quantify wear using rigid body models. Finally, in Chapter 6 the influence of CAS FF on musculoskeletal loading conditions during the patients gait is examined and compared to conventional THR by means of patient-specific musculoskeletal models. All patients were analyzed with highly accurate MoCap gait analysis from which the biomechanical models were built and analyzed during the aforementioned prct at three time points (pre-op, post-op six month, post-op twelve month). In Chapter 7 the thesis is concluded and the main outcome of all studies taken together is discussed.

## References

- [1] W. J. MacLennan. History of arthritis and bone rarefaction evidence from paleopathology onwards. *Scottish medical journal*, 44(1):18–20, February 1999.
- [2] E. Trinkaus. Pathology and the posture of the La Chapelle-aux-Saints Neandertal. *American journal of physical anthropology*, 67(1):19–41, May 1985.
- [3] J. Rogers, I. Watt, and P. Dieppe. Arthritis in Saxon and mediaeval skeletons. *British medical journal (Clinical research ed.)*, 283(6307):1668–70, 1981.
- [4] A. K. Thould and B. T. Thould. Arthritis in Roman Britain. *British medical journal (Clinical research ed.)*, 287(6409):1909–11, 1985.
- [5] P. F. Gomez and J. a. Morcuende. Early attempts at hip arthroplasty–1700s to 1950s. *The Iowa orthopaedic journal*, 25:25–9, January 2005.
- [6] M. Smith-Petersen. Approach to and exposure of the hip joint for mold arthroplasty. *The Journal of Bone & Joint Surgery*, 31(1):40–46, January 1949.
- [7] E. Masterson, B. A. Masri, and D. Clive P. *Revision Total Hip Arthroplasty*. Springer New York, New York, NY, 1999.
- [8] J. Judet and R. Judet. The use of an artificial femoral head for arthroplasty of the hip joint. *The Journal of bone and joint surgery. British volume*, 32-B(2):166–73, May 1950.
- [9] F. R. Thompson. Vitallium intramedullary hip prosthesis, preliminary report. *New York state journal of medicine*, 52(24):3011 – 20, 1953.
- [10] P. Wiles. The surgery of the osteoarthritic hip. *The British journal of surgery*, 45(193):488–97, March 1958.
- [11] G. K. McKee and J. Watson-Farrar. Replacement of arthritic hips by the McKee-Farrar prosthesis. *The Journal of bone and joint surgery. British volume*, 48(2):245–59, May 1966.
- [12] P. A. Ring. Total replacement of the hip joint. *Clinical orthopaedics and related research*, (95):34–7, September 1973.
- [13] J. Charnley. Arthroplasty of the hip - a new operation. *The Lancet*, (1944):1129–1132, 1961.
- [14] I. D. Learmonth, C. Young, and C. Rorabeck. The operation of the century: total hip replacement. *Lancet*, 370(9597):1508–19, October 2007.
- [15] L. Danielsson and H. Lindberg. Prevalence of coxarthrosis in an urban population during four decades. *Clinical orthopaedics and related research*, (342):106–10, September 1997.
- [16] T. P. Vail and J. J. Callaghan. Minimal Incision Total Hip Arthroplasty. *Journal of the American Academy of Orthopaedic Surgeons*, 15(12):707–715, December 2007.
- [17] T. V. Swanson. Posterior single-incision approach to minimally invasive total hip arthroplasty. *International orthopaedics*, 31 Suppl 1:S1–5, August 2007.

- [18] P. J. Duwelius and L. D. Dorr. Minimally invasive total hip arthroplasty: an overview of the results. *Instructional course lectures*, 57:215–22, January 2008.
- [19] J. D. García Juárez, P. A. Bravo Bernabé, A. García Hernández, and O. E. Dávila Sheldon. [Complications on minimal access surgery for total hip arthroplasty]. *Acta ortopédica mexicana*, 22(3):145–9, 2008.
- [20] F. Mouilhade, J. Matsoukis, P. Oger, C. Mandereau, V. Brzakala, and F. Dujardin. Component positioning in primary total hip replacement: a prospective comparative study of two antero-lateral approaches, minimally invasive versus gluteus medius hemimiotomy. *Orthopaedics & traumatology, surgery & research : OTSR*, 97(1):14–21, February 2011.
- [21] C. Mandereau, V. Brzakala, and J. Matsoukis. Functional recovery, complications and CT positioning of total hip replacement performed through a Röttinger anterolateral mini-incision. Review of a continuous series of 103 cases. *Orthopaedics & traumatology, surgery & research : OTSR*, 98(1):8–16, February 2012.
- [22] L. Ogonda, R. Wilson, P. Archbold, M. Lawlor, P. Humphreys, S. O’Brien, and D. Beverland. A minimal-incision technique in total hip arthroplasty does not improve early postoperative outcomes. A prospective, randomized, controlled trial. *The Journal of bone and joint surgery. American volume*, 87(4):701–10, April 2005.
- [23] S. R. Ward, R. E. Jones, W. T. Long, D. J. Thomas, and L. D. Dorr. Functional recovery of muscles after minimally invasive total hip arthroplasty. *Instructional course lectures*, 57:249–54, January 2008.
- [24] M. Wörner, M. Weber, P. Lechler, E. Sendtner, J. Grifka, and T. Renkawitz. [Minimally invasive surgery in total hip arthroplasty : Surgical technique of the future?]. *Der Orthopäde*, 40(12):1068–74, December 2011.
- [25] N. Li, Y. Deng, and L. Chen. Comparison of complications in single-incision minimally invasive THA and conventional THA. *Orthopedics*, 35(8):e1152–8, August 2012.
- [26] B. Yang, H. Li, X. He, G. Wang, and S. Xu. Minimally invasive surgical approaches and traditional total hip arthroplasty: a meta-analysis of radiological and complications outcomes. *PloS one*, 7(5):e37947, January 2012.
- [27] T. Renkawitz, M. Tingart, J. Grifka, E. Sendtner, and T. Kalteis. Computer-assisted total hip arthroplasty: coding the next generation of navigation systems for orthopedic surgery. *Expert review of medical devices*, 6(5):507–14, September 2009.
- [28] W. Y. Shon, T. Baldini, M. G. Peterson, T. M. Wright, and E. A. Salvati. Impingement in total hip arthroplasty a study of retrieved acetabular components. *The Journal of arthroplasty*, 20(4):427–35, June 2005.
- [29] A. Malik, A. Maheshwari, and L. D. Dorr. Impingement with total hip replacement. *The Journal of bone and joint surgery. American volume*, 89(8):1832–42, August 2007.

- [30] S. J. Mellon, G. Grammatopoulos, M. S. Andersen, E. C. Pegg, H. G. Pandit, D. W. Murray, and H. S. Gill. Individual motion patterns during gait and sit-to-stand contribute to edge-loading risk in metal-on-metal hip resurfacing. *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of engineering in medicine*, 227(7):799–810, July 2013.
- [31] K.-H. Widmer and B. Zurfluh. Compliant positioning of total hip components for optimal range of motion. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*, 22(4):815–21, July 2004.
- [32] K.-H. Widmer. Containment versus impingement: finding a compromise for cup placement in total hip arthroplasty. *International orthopaedics*, 31 Suppl 1:S29–33, August 2007.
- [33] L. D. Dorr, A. Malik, M. Dastane, and Z. Wan. Combined anteversion technique for total hip arthroplasty. *Clinical orthopaedics and related research*, 467(1):119–27, January 2009.
- [34] T. Renkawitz, M. Haimerl, L. Dohmen, S. Gneiting, M. Wegner, N. Ehret, C. Buchele, M. Schubert, P. Lechler, M. Woerner, E. Sendtner, T. Schuster, K. Ulm, R. Springorum, and J. Grifka. Minimally invasive computer-navigated total hip arthroplasty, following the concept of femur first and combined anteversion: design of a blinded randomized controlled trial. *BMC Musculoskeletal Disorders*, 12:192, January 2011.
- [35] T. Renkawitz, M. Haimerl, L. Dohmen, S. Gneiting, P. Lechler, M. Woerner, H.-R. Springorum, M. Weber, P. Sussmann, E. Sendtner, and J. Grifka. The association between Femoral Tilt and impingement-free range-of-motion in total hip arthroplasty. *BMC musculoskeletal disorders*, 13(1):65, January 2012.
- [36] T. Renkawitz, M. Haimerl, L. Dohmen, M. Woerner, H.-R. Springorum, E. Sendtner, G. Heers, M. Weber, and J. Grifka. Development and evaluation of an image-free computer-assisted impingement detection technique for total hip arthroplasty. *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of engineering in medicine*, 226(12):911–8, December 2012.
- [37] M. Morlock, E. Schneider, A. Bluhm, M. Vollmer, G. Bergmann, V. Müller, and M. Honl. Duration and frequency of every day activities in total hip patients. *Journal of biomechanics*, 34(7):873–81, July 2001.
- [38] M. U. de Rezende and G. C. de Campos. Is osteoarthritis a mechanical or inflammatory disease? *Revista Brasileira de Ortopedia (English Edition)*, 2013.
- [39] M. P. Clapper and S. L. Wolf. Comparison of the reliability of the Orthoranger and the standard goniometer for assessing active lower extremity range of motion. *Physical therapy*, 68(2):214–8, February 1988.
- [40] M. S. Madsen, M. A. Ritter, H. H. Morris, J. B. Meding, M. E. Berend, P. M. Faris, and V. G. Vardaxis. The effect of total hip arthroplasty surgical approach on gait. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society*, 22(1):44–50, January 2004.

- [41] G. M. Whatling, H. V. Dabke, C. A. Holt, L. Jones, J. Madete, P. M. Alderman, and P. Roberts. Objective functional assessment of total hip arthroplasty following two common surgical approaches: the posterior and direct lateral approaches. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 222(6):897–905, June 2008.
- [42] R. Baker. *Measuring Walking: A Handbook of Clinical Gait Analysis*. Mac Keith Press; Auflage: 1, 2013.
- [43] K. C. Foucher, M. A. Wimmer, K. C. Moio, M. Hildebrand, M. C. Berli, M. R. Walker, R. A. Berger, and J. O. Galante. Time course and extent of functional recovery during the first postoperative year after minimally invasive total hip arthroplasty with two different surgical approaches—a randomized controlled trial. *Journal of Biomechanics*, 44(3):372–378, February 2011.
- [44] I. H. F. Reininga, R. Wagenmakers, I. van den Akker-Scheek, A. D. Stant, J. W. Groothoff, S. K. Bulstra, W. Zijlstra, and M. Stevens. Effectiveness of computer-navigated minimally invasive total hip surgery compared to conventional total hip arthroplasty: design of a randomized controlled trial. *BMC musculoskeletal disorders*, 8:4, January 2007.
- [45] R. N. Stauffer, G. L. Smidt, and J. B. Wadsworth. Clinical and biomechanical analysis of gait following Charnley total hip replacement. *Clinical orthopaedics and related research*, 99(99):70–7, 1974.
- [46] Hermens, Freriks, Merletti, Stegemann, Blok, Rau, Disselhorst-Klug, and Hägg. *Seniam-European Recommendations for Surface ElectroMyoGraphy -Results of SENIAM Project*. 1999.
- [47] K. M. Barr, A. L. Miller, and K. B. Chapin. Surface electromyography does not accurately reflect rectus femoris activity during gait: impact of speed and crouch on vasti-to-rectus crosstalk. *Gait & posture*, 32(3):363–8, July 2010.
- [48] G. Bergmann, G. Deuretzbacher, M. Heller, F. Graichen, A. Rohlmann, J. Strauss, and G. N. Duda. Hip contact forces and gait patterns from routine activities. *Journal of biomechanics*, 34(7):859–71, July 2001.
- [49] E. J. Bassey, J. J. Littlewood, and S. J. Taylor. Relations between compressive axial forces in an instrumented massive femoral implant, ground reaction forces, and integrated electromyographs from vastus lateralis during various 'osteogenic' exercises. *Journal of biomechanics*, 30(3):213–23, March 1997.
- [50] V. Correia, V. Sencadas, M. Martins, C. Ribeiro, P. Alpuim, J. Rocha, I. Morales, C. Atienza, and S. Lanceros-Mendez. Piezoresistive sensors for force mapping of hip-prostheses. *Sensors and Actuators A: Physical*, 195:133–138, June 2013.
- [51] F. Pauwels. [Short survey of mechanical stress of bone and its importance for the functional adaptation (author's transl)]. *Zeitschrift für Orthopädie und ihre Grenzgebiete*, 111(5):681–705, October 1973.

- [52] S. Blumentritt. [The relationship between the gait of humans and the hip joint structure in the frontal plane]. *Gegenbaurs morphologisches Jahrbuch*, 136(6):677–93, January 1990.
- [53] J. Rasmussen, M. Damsgaard, and M. Voigt. Muscle recruitment by the min/max criterion – a comparative numerical study. *Journal of biomechanics*, 34(3):409–15, March 2001.
- [54] M. Damsgaard, J. Rasmussen, S. r. T. r. Christensen, E. Surma, and M. de Zee. Analysis of musculoskeletal systems in the AnyBody Modeling System. *Simulation Modelling Practice and Theory*, 14(8):1100–1111, November 2006.
- [55] M. de Zee, M. Dalstra, P. M. Cattaneo, J. Rasmussen, P. Svensson, and B. Melsen. Validation of a musculo-skeletal model of the mandible and its application to mandibular distraction osteogenesis. *Journal of biomechanics*, 40(6):1192–201, January 2007.
- [56] M. E. Lund, M. de Zee, M. S. Andersen, and J. Rasmussen. On validation of multibody musculoskeletal models. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 226(2):82–94, January 2012.
- [57] S. J. Mellon, M. S. Andersen, G. Grammatopoulos, and H. S. Gill. Mal-positioning alone does not necessarily lead to increased wear in metal-on-metal hip resurfacing. *ORS 2012 annual meeting*, 79(6):2011, 2012.
- [58] T. Weber, S. Dendorfer, S. Dullien, J. Grifka, G. J. Verkerke, and T. Renkawitz. Measuring functional outcome after total hip replacement with subject-specific hip joint loading. *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of engineering in medicine*, 226(12):939–46, December 2012.
- [59] F. C. Anderson and M. G. Pandy. Static and dynamic optimization solutions for gait are practically equivalent. *Journal of biomechanics*, 34(2):153–61, March 2001.