

# Surgical Workflow Simulation for the Design and Assessment of Operating Room Setups in Orthopedic Surgery

Juliane Neumann (✉ [Juliane.Neumann@medizin.uni-leipzig.de](mailto:Juliane.Neumann@medizin.uni-leipzig.de))

Universität Leipzig <https://orcid.org/0000-0002-5696-9473>

Christine Angrick

Universität Leipzig Medizinische Fakultät

Celina Höhn

Universität Leipzig Medizinische Fakultät

Dirk Zajonz

Universitätsklinikum Leipzig

Mohamed Ghanem

Universitätsklinikum Leipzig

Andreas Roth

Universitätsklinikum Leipzig

Thomas Neumuth

Universität Leipzig Medizinische Fakultät

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## Research article

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# Abstract

**Background** The design and internal layout of modern operating rooms are influencing the team's collaboration and communication, ergonomics, as well as intraoperative hygiene substantially. Nevertheless, there is no objective method for the assessment and design of the personnel and table positions for different surgical disciplines and intervention types available. The aim of this work is to establish an optimal OR setup for common procedures in arthroplasty.

**Methods** With the help of computer simulation techniques, a method for the objective design and assessment of optimal OR setups was developed. In this work, new OR setups were designed, analyzed in a computer simulation environment and evaluated in the actual intraoperative setting.

**Results** It was shown that the implementation of an optimized OR setup reduces the intraoperative instrument handover time between the surgeon and the scrub nurse, the travel paths of the OR team as well as shorten the procedure duration. Additionally, the ergonomics of the OR staff could be improved.

**Conclusion** The developed simulation method was intraoperatively evaluated and proved its benefit for the design and optimization of OR setups for different surgical intervention types. As a clinical result, optimized setups for total knee arthroplasty and total hip arthroplasty surgeries were established in daily clinical routine and the OR efficiency was improved.

## Background

The efficient design and layout of operating rooms (OR) is in the focus of surgeons and architects for several decades [1],[2]. Since the 19<sup>th</sup> century, the OR design has changed from anatomy theatres with visitor galleries to a highly aseptic and technical environment [2]. The integration of large-scale medical devices (e.g. intraoperative MRI or X-ray devices) and innovative surgical methods (e.g. minimal invasive and robotic surgery) in the OR lead to an increase of the operating room size in recent years [3]. As the ORs become larger, also the spatial distances in the OR and between functional units such as supply areas, sterilization as well as anesthesia and post-anesthesia care units increase. This results in inefficient perioperative processes and long travel paths for the OR staff. Thus, the medical and technical equipment and surgical department layout also have an essential impact on the intraoperative processes and therefore the overall efficiency of the surgical procedures. For a good reason, the resource-intensive surgical department is in the focus of continuous optimization in order to create an efficient and safe environment for optimal patient treatment.

The optimal layout of surgical departments has been widely analyzed from different perspectives, e.g. patient flow [4],[5], efficiency and economics [6],[7] hygiene [8], and equipment [9]. Research regarding the design of the internal OR layout in respect of OR and instrument tables as well as staff positions has been given little to no consideration. Attempts to determine the optimal design for special interventions, such as hybrid ORs [3],[10] and endoscopic surgery suites [11] were reported. However, there is no objective method for the assessment and design of the personnel and table positions for different

surgical disciplines and intervention types available. Although, the OR setup is influencing the team's collaboration and communication [12], ergonomics, as well as intraoperative hygiene substantially, the table layout is set up mostly based on the subjective preference of the lead surgeon or based on institutional practices.

The aim of this work is to establish an optimal OR setup for common procedures of orthopedic surgery. Thereby, we focused on the efficient OR team's collaborative surgical processes and ergonomics. The positions of the OR team and instrument tables as well as optimal travel paths in the OR were considered. With the help of computer simulation techniques, a method for the objective design and assessment of an optimal OR setup was developed, which could be applied to other surgical disciplines and intervention types. Subsequently, the defined OR setups were evaluated regarding their impact on the surgical processes and overall efficiency of the procedure. The objective was to optimize the intraoperative processes and consequently reduce the procedure duration by optimizing the OR layout to increase the number of performed surgeries and improve the utilization of available OR capacities.

## Material And Methods

For the development of optimized OR setups, an objective methodology was designed and is presented in Figure 1. Firstly, for two different clinical procedures (section 2.1) various intraoperative data were acquired (section 2.2) for assessment of the operating room setups. In addition, an ergonomic assessment of the surgical team was performed (section 2.3). Based on the acquired intraoperative and ergonomic data, requirements for an optimal OR setup were defined, and new OR setups for orthopedic surgery were designed (section 2.4). With the help of computer simulation methods (section 2.5), the simulation results were analyzed from different perspectives and evaluated in the actual intraoperative setting (section 2.6).

Figure 1- Methodology for the objective design and assessment of optimal OR setups

## 2.1 Clinical Procedure

Total Hip Arthroplasty (THA) and Total Knee Arthroplasty (TKA) surgeries were defined as a use case within this study. In THA surgeries, the hip joint is replaced by a prosthetic implant to treat arthritis pain or hip fractures. With over 1.4 million cases per year [13], it is one of the most performed surgeries worldwide. During TKA the knee joint is replaced to relieve debilitating pain or osteoarthritis. TKA is with 1.1 million cases per year worldwide, also a highly performed procedure [14]. Although surgical implants surgeries bear a high risk for surgical site infections, the infection rates are less common than e.g. catheter-related infections [15]. Nevertheless, the treatment of implant infections is complex, longer and more cost-intensive [15],[16]. Therefore, intraoperative hygiene for THA and TKA surgeries is in the focus of continuous consideration and optimization. Besides hygienic aspects, also economic and ergonomic considerations are highly relevant during OR layout design for THA and TKA surgeries.

## 2.2 Data Acquisition of Orthopedic Procedures and Current OR Setups

Initially, 15 THA and 7 TKA surgeries were recorded at the University of Leipzig Medical Center, Division of Endoprothetic Joint Surgery and General Orthopaedics in 2016 for the intraoperative process and setup optimization. During process acquisition, the intraoperative processes for THA and TKA were manually recorded with a low granularity level. Thereby, the duration of the surgery (incision-to-begin-of-closure time (IBCT)), as well as the used OR setups for THA and TKA with positions of instrument tables and the position of the OR staff, were acquired. For every OR setup the amount, duration and pathway of instrument hand-over between the surgeon and scrub nurse were measured. The organization of instruments on the table is not considered in this study. Furthermore, the pathways of the circulator were recorded for every THA and TKA OR setup.

The ground plan of the orthopedic OR at the University of Leipzig Medical Center was digitized for the modeling in the simulation environment (Figure 3). Additionally, dimensions of furnishing, OR table (fixed position in the OR), instrument tables (mayo stands, instrument/equipment stands, solutions stands, etc.), medical devices (e.g. c-arm and anesthesia equipment) as well as OR display were acquired. The dimensions were integrated into the 3D computer simulation model to create a realistic image of the orthopedic OR.

## 2.3 Ergonomic Assessment

### Ovako Working Posture Analyzing System

The ergonomic assessment of the initial OR setups for THA and TKA was performed using the *Ovako Working Posture Analyzing System* (OWAS). The method was developed by Karhu et al. in 1977 [17] and is used to ergonomically classify working postures of the back, arms, legs and optionally the head. For the ergonomic evaluation of the operating room theatres, OWAS was already used for different surgical disciplines [13],[18],[19] as well as different occupational groups, like surgeons [20] and scrub nurses [21].

Especially, orthopedic surgeons have an increased risk of musculoskeletal injuries and disorders due to the more physical demands of the surgeries [22],[23]. To address this problem, the intraoperative situation in the orthopedic OR should be improved. Therefore, the OWAS assessment was performed for the surgeon, assistants, scrub nurse and the circulator in THA and TKA surgery for the initial OR setups. A detailed analysis of the ergonomic situation in the orthopedic OR as well as all results of the OWAS assessment can be found in [24]. The evaluation results showed ergonomic critical positions most of the time for the surgeon, the scrub nurse and the assistants regarding bent or twisted back and head postures as well as static positions and prolonged standing during surgery. Based on the findings of the OWAS assessment, requirements for ergonomically optimized OR setups were defined and improved OR setups were designed.

## Total Rotational Movement (TRM)

In addition to the OWAS assessment, the amount of rotational movement, which is performed by the surgeon and the scrub nurse during an instrument handover, was calculated with a simplified theoretical model. The body rotation depends significantly on the OR setup and has a great impact on the staffs' ergonomics. The theoretical degree of rotation was calculated for each OR setup by determining and adding the angles between the tables and persons for an instrument handover. For simplicity, it has been assumed that the scrub nurse rotates the torso according to the instrument tables' angle. The *Total Rotational Movement of an OR table*  $TRM_{Table}$  is defined as

[Due to technical limitations, this equation is only available as a download in the supplemental files section.]

$\alpha$  may be the angle of rotational movement of the scrub nurse for grabbing an instrument from an instrument table.  $\beta$  is defined as the rotation angle of the scrub nurse for giving the instrument to the surgeon and  $\gamma$  is the angle of the surgeons' rotational movement for grabbing the instrument from the scrub nurse. Be  $i$ ,  $j$ , and  $k$  the number of movements for one rotational movement. In most cases, the person needs to move two times—firstly, to the target (table or person) and secondly back in the original position. The Total Rational Movement of the OR setup is the sum of the overall  $TRM_{Table}$ . In Figure 2 an example of the rotational model for a left-side THA OR setup is presented.

Figure 2 - Example of the simplified theoretical model to calculate the Total Rotational Movement of an OR setup, including the scrub nurse (left) and surgeon (right)

## 2.4 Design of New OR Setups for THA and TKA

The positioning of the OR table, instrument tables, and the OR personnel is mostly defined by the preference of the main surgeon or the scrub nurse. Even for the same intervention type in the same institution, there are often different OR setups implemented. The OR layout is affecting the surgical processes, the staffs ergonomic as well as team collaboration in the OR. For example, the impact of instrument table positions on the surgeon and scrub nurse instrument transfer performance was analyzed in [12]. It could have shown that the alignment (gaze direction) and the relative position of the table in the proximity of the surgeon have an influence on the handover time [12].

However, current research lacks in the objective determination of how an optimal OR setup could be defined for different intervention types and surgical disciplines and which aspects need to be considered in the design phase. Due to the lack of literature, a non-deterministic list of requirements was identified with the help of ergonomic assessment, process analysis, and clinical expert interviews. For this purpose, 22 orthopedic procedures were observed in respect to their functional, spatial and ergonomic requirements. Additionally, a brain-storming workshop with 3 experienced senior surgeons and 5 scrub nurses was conducted to define the requirements of an optimal OR setup. The identified aspects are presented in Table 1 and should be considered in the design and lay outing of OR setups.

Considering these aspects as well as the results of the OWAS and TRM assessment, improved OR layouts for THA and TKA surgeries were designed and implemented in the simulation environment for evaluation. The initially recorded setups, which were used at the University of Leipzig Medical Center, were compared with the improved setups to determine an optimal intra-OR layout for THA and TKA surgeries.

## 2.5 Discrete Event Simulation

For the optimization of the internal OR layout, Discrete Event Simulation (DES) was utilized, which is a methodology to (re-) design, analyze, execute and evaluate processes in respect of different situations or objectives. DES enables the emulation and prediction of changes in a dynamic model of a real-world system over time via mathematical modeling [26]. The simulation allows a safely and repeatedly analysis of a situation and the impact of different parameters and process configurations on the process, e.g. methods and strategies, process alternatives, different activity durations or availability of personnel and material resources [27].

DES relies on the modeling of systems with a list of events, which are usually described with instructions and logic for executing the simulation. During the simulation, the modeled processes are executed by processing transitions between the events. For mathematical modeling, acquired data of process times and activity rates are needed [28],[29]. There are two commonly used approaches for simulation execution in DES. In *Event Scheduling*, the process is sampled by the simulation environment from events with predefined distributions of times [28]. In *Process Interaction*, the process is described as a chronological and sequential order of events. Process Interactions is a commonly used modeling approach and is also mainly supported by commercial simulation tools. With both approaches, DES methods are suitable for simulation in healthcare and especially in the OR [30],[31].

Computer simulation has been widely used for the representation, analysis, optimization, and prediction of hospital and OR processes. In hospital management, simulation has been applied for the analysis and optimization of pathway and workflow planning [32], optimization of patient flow [33] and resource planning [34]. In the OR setting, simulation methods have been also utilized, mainly to optimize the OR scheduling and patient flow improvement [5],[26],[35],[36]. In the domain of intraoperative process optimization, Fernández-Gutiérrez et al. used DES methods in order to find the optimal development of new complex procedures in multimodal imaging environments [37] and for resource optimization of medical equipment [38]. To the best of our knowledge, DES methods have not been utilized yet for the objective design of an optimal OR layout.

## Simulation Software

Following the argumentation in [38], Delmia by Dassault Systèmes [39] was used to simulate THA and TKA intraoperative processes and an optimal OR setup for these interventions was determined. Delmia provides a 3D Modeling environment and a logical process simulation component. Although Delmia was

originally developed for the simulation of manufacturing processes, it has also wide distribution in healthcare (e.g. [5],[38]). Delmia consists of tree modeling perspectives. The *CAD world* enables the creation and import of 3D objects. The *Model world* allows the graphical implementation of the models and the *Simulation world* contains the simulation and program logic for the process execution of the model.

Figure 3—Example of a Delmia 3D simulation model (left-side THA Setup 1)

## CAD and Workflow Modeling

In the first step, a 3D model of the orthopedic OR including the furnishing was created based on the ORs' ground plan and on-site measurements of the inventory. Subsequently, the 3D CAD model of the OR is then accessed from the Model world, which enables a graphical implementation of the model. To create a realistic digital OR simulation environment for the evaluation of OR setups, the CAD models were enriched with 3D representations of the OR staff and material resources (e.g. instrument tables and instruments, displays, the OR table as well as medical devices). In the Model world, the graphical representation is based on accurate 3D geometries, which enable the integration of geometric measurements in the simulation and process analysis. For the simulation, the model elements need to be provided with details about their behavior during process executions (e.g. location, activities, speed, process duration).

The intraoperatively recorded processes of THA and TKA surgeries were modeled in Delmia with Process interaction methods. Consequently, the model elements were enriched with process logic and the initially recorded process parameters (e.g. the amount and duration of instrument handovers, surgery duration or the circulators' travel path) to evaluate alternative OR layouts in different simulation studies.

## Simulation Studies

For every recorded and newly designed OR setup, a simulation model was created with Delmia. Figure 3 shows an example of the Delmia simulation environment with a 3D model of the orthopedic OR for a left-side THA setup. Due to the different setups according to the operated leg of the patient, in each case, a left-side and right-side setup were modeled. This results in 6 THA simulation models (2 initial setups and 1 newly designed setup) and 8 TKA simulation models (1 initial setup and 3 newly designed setups). For all models, a simulation study was performed in which the surgical processes were analyzed from different perspectives.

## Instrument Handover Times

During data acquisition, the number and pathway of instrument handovers between surgeon and scrub nurse as well as the handover time were measured for different OR tables in the initial setups. Thereby a mean handover speed was calculated with Delmia, which is also the base for the handover simulation in

the newly designed OR setups. The adequate number of instrument handovers were performed in the simulation environment and the resulting handover time, as well as the total handover time of one surgery, was calculated by Delmia.

## **Travel Path of the Circulator**

In every simulation scenario, the travel path of the circulator was calculated and combined with the instrument handover process simulation. During process acquisition, the number and pathways for each way, e.g. to a supply stock or to the scrub nurse for material handover, were recorded. The optimal pathways of the circulator to different destinations varied according to the optimal travel path through the actual OR setup. With the help of Delmia, it was possible to determine the total distance, which was traveled by the circulator during a THA or TKA surgery.

## **2.6 Evaluation of the Simulation Results**

The THA and TKA setup, which performed best in the simulation scenario was implemented in the orthopedic OR. Thereby, in 2018 15 THA and 14 TKA surgeries were recorded at the Division of Endoprothetic Joint Surgery and General Orthopaedics at the University of Leipzig Medical Center. The number and duration of instrument handover, the incision-to-begin-of-closure time (IBCT) as well as the incision-to-closure-time were recorded for every surgery. In further data analysis and setup evaluation, only the surgery duration until the end of the last interventional activity and the begin of the suturing is considered. The suturing is often performed by a novice, which results in a higher amount of instrument handovers and longer durations for suturing. Therefore, only the IBCT is considered to ensure better comparability. Subsequently, the data were compared with the simulation results and evaluated against the data, recorded in the initial THA and TKA setups.

## **Results**

### **3.1 OR Setups for Total Knee Replacement**

#### **Initial TKA Setup 1**

During data acquisition, the initial TKA Setup 1 was used with minor variations in the position of the 1<sup>st</sup> assistant in every TKA surgery at the orthopedic department. In the left-side TKA Setup 1 (Figure 4, left) the scrub nurse (SN), surgeon (SU) and the 1<sup>st</sup> assistant (A1) stand on the left side of the OR table as seen by the patient. The A1 stands either on the same site as the surgeon or together with the 2<sup>nd</sup> assistant (A2) on the opposite. The instrument tables 1–4 are located at the lower end of the OR table in a U-shape around the scrub nurse. In some surgeries, table 5 is used as a backup table. The c-arm is used during surgery for the evaluation of the implant position. It is located behind the A2 and is brought to the

right side of the OR table when needed. The setup is mirrored along the operating table for the right-side TKA (Figure 4, right).

Figure 4 - Schematic representation of the left side TKA Setup 1 (left) and right-side TKA Setup 1 (right), (SN—scrub nurse; SU—surgeon; A1, A2—1<sup>st</sup> and 2<sup>nd</sup> assistant; AN—anesthesiologist; R1,R2—rack with materials and supplies; WP1, WP2—working place with displays; AR—anesthesia room)

A beneficial factor is that the scrub nurse has a direct view of the operating area and has a good position for the instrument handover with the surgeon. Disadvantages arise from the need of the scrub nurse to turn around to reach tables 2, 3 and 4. Thereby, the direct view to the surgeon and the operating area is blocked. In the right-side setup, the instrument tables are close to the working place (WP1), which indicates that the circulator is often passing the instrument tables nearby. This entails air movement and a potential threat to the sterility of the instruments and implants. For the left-side setup, there is also little space between the WP1 and table 2 and 3, when the circulator is going to the sterile room on the left side of the OR.

## **Newly designed TKA Setup 2**

In this newly designed left-side TKA setup (Figure 5, left) the rotational movement of the scrub nurse should be reduced by arranging the instrument tables in a U-shape behind the surgeon. Thereby, tables 1 and 2 are located between the scrub nurse and the surgeon. Table 3 and 4 are located on the left and on the right side of the scrub nurse.

Figure 5 - Schematic representation of the left-side TKA Setup 2 (left) and the right-side TKA Setup 2

In the right-side setup (Figure 5, right) there is little space for the circulator between the WP1 and the instrument tables. In the left-side setup, workplace 2 is almost completely blocked by an instrument table. In addition, the travel path is entirely impassable to one side, but all destinations can be reached. Another disadvantage is that the scrub nurse stands behind the surgeon, which leads to an increase in rotational movements of the surgeon and possibly has a negative impact on the hygiene. Nevertheless, the setup was considered for further evaluations.

## **Newly designed TKA Setup 3**

The goal of the TKA Setup 3 design was to maintain the compact table layout of Setup 2 but to establish a direct view between the surgeon and the scrub nurse as well as the operating area. Therefore, in the left-side TKA Setup 3 (Figure 6, left) the instrument tables are located in a U-shape around the scrub nurse at the bottom of the OR table. The scrub nurse faces the surgeon directly and has a direct view of the operating area. The circulator can reach all workplaces and supply storages without any obstructions. The right-side TKA Setup 3 (Figure 6, right) is mirrored along the operating table.

Figure 6 - Schematic representation of the left-side TKA Setup 3 (left) and right-side TKA Setup 3 (right)

## Newly designed TKA Setup 4

Figure 7 - Schematic representation of the left-side TKA Setup 4 (left) and right-side TKA Setup 4

The newly designed TKA Setup 4 is inspired by the table layout of the initial TKA Setup 1, but the setup differs in the position of the scrub nurse. In the new TKA Setup 4 (Figure 7) the scrub nurse is facing the surgeon by standing on the opposite of the OR table, instead of next to the surgeon. Thus, a direct view can be established between the two persons and the operating area is also directly visible to the scrub nurse. This does not solve the problem that the scrub nurses' view is blocked when turning to table 3 and 4. In addition, the tables are close to the WP1 of the circulator.

## 3.2 OR Setups for Total Hip Replacement the orthopedic OR

### Initial THA Setup 1

For left-side THA (Figure 8, left), the scrub nurse, the surgeon, and the 1<sup>st</sup> assistant are positioned on the left side of the patient's body, while the 2<sup>nd</sup> assistant stands on the right side (healthy hip joint). The surgeon stands at the patient's hip. The four tables are arranged in a J-shape around the scrub nurse at foot of the OR table with one table in front, on the left side and two tables behind. The right-side THA Setup 1 is mirrored along the operating table (Figure 8, right).

The main advantage is that the scrub nurse is in a good position to the surgeon for instrument hand over. Thus, the direct view of the operating area is occasionally limited when the surgeon turns to the patient or the scrub nurse turns to table 2, 3 and 4. For right-side THA setup, the instrument tables are located with less than 1m distance to the WP1, which can affect the sterility of the instrument tables. For the left-side THA setup, there is also little space between WP2 and table 4, which impedes the direct travel path of the circulator to the supply storage (R1 and R2) as well as the working place 2 (WP2).

Figure 8 - Schematic representation of the left-side THA Setup 1 (left) and right-side THA Setup 1 (right)

### Initial THA Setup 2

In the second recorded THA setup, there are only three instrument tables, which are arranged in a U-shape around the scrub nurse behind the surgeon with table 1 between them. The use of a 3-table or 4-table setup depends on the preferences of the OR team as well as resource requirements and the complexity of the surgery. In principle, a 3-table setup is sufficient for most of the THA surgeries. Therefore, an additional table is positioned on the left side and one on the right side of the scrub nurse. For left-side THA (Figure 9, left), the surgeon, scrub nurse, and the 1<sup>st</sup> assistant are located on the left side of the

patient and the 2<sup>nd</sup> assistant stands on the right side. For right-side THA the OR setup is mirrored along the OR table (Figure 9, right).

Figure 9 - Schematic representation of the left-side THA Setup 2 (left) and the right-side THA Setup 2

In the initial THA Setup 2, half of the OR is blocked for the circulator, but the travel paths to the anesthesia room on the right side and the sterile room on the left side of the OR can be reached without close proximity to the operating area and the instrument tables. Another advantage is that the scrub nurse has a direct view of the operating area and the surgeon even when turning to table 2 and 3. The slight drawback of the setup is that the surgeon has to turn around for every instrument handover.

## Newly designed THA Setup 3

For THA surgery one OR setup is newly designed with only three instrument tables. In the left-side THA Setup 3 (Figure 10, left), the instrument tables are located around the scrub nurse. Table 2 is positioned directly at the bottom of the OR table. Table 1 stands between the scrub nurse and the surgeon. Additionally, table 3 closes the U-shaped arrangement around the scrub nurse, who is facing the surgeon directly. The circulator has unrestricted access to all supply stocks and workplaces. For right-side THA (Figure 10, right), the setup is mirrored along the operating table.

Figure 10 - Schematic representation of the left-side THA Setup 3 (left) and right-side THA Setup 3 (right)

## 3.3 In Silico Comparison of Initial and Newly Designed OR Setups

### Instrument Handover Times

The instrument handovers for all tables in all TKA setups were simulated with Delmia and subsequently compared with each other (Figure 11, left side). As a result, Setup 3 enables the fastest instrument handover between scrub nurse and surgeon for tables 1, 2 and 4. For table 3 Setup 2 allows a slightly faster handover. Setup 1 and Setup 4 have equivalent instrument handover times due to the similar setup design whereby Setup 4 is slightly faster for the tables 1, 2 and 4.

Figure 11 - Comparison of Delmia simulation results for the instrument handover times of the TKA Setups 1–4 and tables 1–4 (left side) and THA Setups 1–3 and tables 1–4 (right side)

For all tables and THA setups, the instrument handover times were also simulated with Delmia and then compared with each other (Figure 11, right). The newly designed Setup 3 enables the fastest instrument handover between the surgeon and the scrub nurse for all tables.

## Total Instrument Handover Times

During initial data acquisition, the total number of instrument handovers and the handover path in 7 TKA surgeries, were recorded in the initial TKA Setup 1. For table 1 an average of  $108.3 \pm 32.2$  instrument handovers, for table 2 an average of  $5.7 \pm 7.3$  handovers, for table 3 an average of  $5.0 \pm 4.2$  handovers and for the table 4 an average of  $2.7 \pm 2.3$  instrument handovers were documented. Based on the number of handovers, the total handover time was calculated in the Delmia simulation scenarios for right-side and left-side TKA setups (Figure 12, left). As a result, Setup 3 performed best with a total instrument handover time of 91.8 seconds. Setup 2 was the slowest setup in the simulation. There was no measurable difference between right-side and left-side setup in the simulation of total instrument handover times.

Figure 12 - Comparison of Delmia simulation results of the total instrument handover time for the TKA Setups 1–4 (left side) and THA Setups 1–3 (right side)

For the THA interventions, the total number of instrument handovers and the handover path were recorded. Thereby, 9 THA surgeries with Setup 1 and 6 THA surgeries with Setup 2 were recorded. In Setup 1, an average of  $60,8 \pm 19.1$  instrument handovers was recorded from table 1,  $2.2 \pm 2.5$  handovers from table 2,  $1.7 \pm 1.5$  handovers from table 3 and  $1.4 \pm 2.5$  handovers from table 4. In Setup 2, an average of  $71.7 \pm 22.6$  instrument handovers was recorded from table 1,  $9.2 \pm 8.5$  from table 2 and  $0.3 \pm 0.8$  handovers from table 3. Based on the average handovers from Setup 1 and Setup 2, the total handover time was calculated with Delmia for right-side and left-side THA setups (Figure 12, right). In the simulation scenario, Setup 3 performed best with a total instrument handover time of 62.6 seconds.

## Distance Traveled by the Circulator

During the initial data acquisition, the number and pathways of the circulator were recorded in the 7 TKA surgeries. Thereby, the circulator travels on average  $4.0 \pm 1.6$  times to the supply rack R1,  $2.7 \pm 2.0$  times to supply rack R2,  $2.7 \pm 1.4$  times to the supply stock ST1, which is located outside of the OR,  $3.0 \pm 0.8$  times to the supply stock ST2, which is located in the sterile room on the left side of the OR and  $2.2 \pm 1.2$  times to the anesthesia room on the right side of the OR. Additionally, the circulator walks on average  $7.6 \pm 3.0$  times to the scrub nurse to hand over sterile supplies or for the support of material opening.

Figure 13 - Total distance traveled by the circulator during one surgery with TKA Setup 1–4 (left side) and THA Setup 1–3 (right side)

The simulation results of the traveled distance (Figure 13, left) showed that there are only slight differences between the setups. The walking distance is marginally longer, mainly for the left-side TKA, if the instrument tables are blocking the pathway between the WP1 and the scrub nurse as well as the supply racks R1 and R2. Setup 3 provides the best balance of left-side and right-side setup. Thus, the travel paths do not differ for left-side and right-side TKA, since the position of the tables does not change as a result of the mirroring.

In the right side of Figure 13, the total distance traveled by the circulator during a THA surgery is presented. The number of pathways was recorded in 15 THA surgeries. The circulator travels on average  $2.6 \pm 2.9$  times to the supply rack R1,  $1.5 \pm 1.1$  times to the supply rack R2,  $0.3 \pm 6.6$  times to the supply stock ST1,  $4.5 \pm 2.3$  times to the supply stock ST2 and  $2.3 \pm 1.6$  times to the anesthesia room as well as  $5.0 \pm 4.7$  times to the scrub nurse. As a result of the Delmia simulation scenario, the walking distance of the left-side THA Setup 3 is the shortest. For the right-side Setup 3, it is marginally longer than Setup 1 and the right-side Setup 2. For the right-side THA Setup 3, the circulator needs to go around the operating room table due to a blocked passage on the left side of the OR, which leads to a slightly longer pathway compared to the initial Setups 1 and 2.

## Total Rotational Movement

In the left-side Figure 14, the TRM for all TKA setups is presented. For the initially recorded Setup 1, the theoretically calculated TRM is  $1890^\circ$  (Setup 1a - rotation to right side) and  $2070^\circ$  (Setup 1b - rotation to left side), for the newly designed Setup 2 the TRM is  $1800^\circ$  and for Setup 4 the TRM is  $1350^\circ$  (Setup 4a - rotation to right side) and  $1215^\circ$  (Setup 4b - rotation to left side). Setup 3 has the lowest TRM with  $1170^\circ$  and seems to be the most balanced solution between the TRM of the surgeon and the scrub nurse.

Figure 14 - Total Rotational Movement for the TKA Setups 1a–4b and THA Setups 1a–3. Setups marked with *a* are calculated with a rotation to the right side and Setups marked with *b* are calculated with a rotation to the left-side

The TRM of all THA setups is presented in right-side Figure 14. For the initially recorded Setup 1, the TRM is  $1890^\circ$  (Setup 1a - rotation the right side) and  $2070^\circ$  (Setup 1b - rotation to left side) and for Setup 2 the TRM is  $1140^\circ$  for every instrument hand over. The newly designed Setup 3 has the lowest TRM with  $900^\circ$  and provides a good balance between the TRM of the surgeon and the scrub nurse.

## 3.4 Evaluation of the Best-performing Setup in the Actual Intraoperative OR Environment

For TKA surgery, Setup 3 seemed to be the best option of all analyzed TKA setups. Instrument handover times, TRM, as well as the travel paths of the circulator, performed better than the other designed setups and the initial Setup 1. The tables are arranged in a U-shape around the scrub nurse at the bottom of the OR table. Beneficially, the scrub nurse faces the surgeon directly and has a direct view on the operating area. Furthermore, the circulator can reach all workplaces and supply storages without any obstructions. The instrument table setup was discussed with the surgical team of the Division of Joint Replacement and Orthopedics and a final adaptation was made before the setup was implemented in the actual OR and daily clinical routine. This led to a slightly adapted OR layout with only 3 instrument tables for TKA surgery (Figure 15).

Figure 15 - Schematic representation of the final TKA Setup 3, which was evaluated in the actual OR setting

For THA surgery, also Setup 3 seems to be the best option of the analyzed setups. The single and the total instrument handover times, TRM, as well as travel paths of the circulator, showed better results than both initial setups. In Setup 3 the three instrument tables are arranged in U-shape around the scrub nurse at the bottom of the OR table. The scrub nurse faces the surgeon and has a direct view of the operating area. Additionally, the circulator has unrestricted access to all destinations.

Setup 3 was also discussed with the orthopedic OR team before it was implemented in the intraoperative OR environment. Thereby, a working method for the position change of the surgeon and the 1<sup>st</sup> assistant was identified (Figure 16). The challenge was the rearrangement of the instrument tables during insertion of the femur part of the hip implant. The scrub nurse should be able to reach the surgeon within an arm length, although the 1<sup>st</sup> assistant stands between them. For this purpose, the scrub nurse pushes the instrument tables 1 and 3 (left-side THA) respectively tables 1 and 2 (right-side THA) forward between the 1<sup>st</sup> assistant and the surgeon. Thereby, all instruments needed for the insertion of the femur implant need to be available at the two moving tables. After the femur implant is inserted, the surgeon, 1<sup>st</sup> assistant and scrub nurse change back to the initial position.

Figure 16 - Schematic representation of the final left and right-side THA Setup 3 during position change of the surgeon and 1<sup>st</sup> assistant

The setups, which performed best in the simulation scenarios, were evaluated in the actual intraoperative OR environment and additionally 14 TKA and 15 THA were recorded. Therefore, the time of instrument handovers, as well as the IBCT, were documented and compared to the initial intraoperative data.

## Instrument Handover Times

Firstly, the instrument handover times of the new TKA setup were compared to the initial measured data of the TKA Setup 1 (Figure 17, left). The tables 1 and 2 were combined in the final TKA Setup 3 (Figure 15) to one 0°-table. Consequently, the measured handover times of the initial Setup 1 for table 1 (0°) and 2 (45°) were merged for better comparability with the new three-table TKA setup. The 90° table in TKA Setup 1 was compared with the left-side 90° table 2 in Setup 3. Since the 180° instrument table in Setup 1 and the right-side 90° table in Setup 3 involve the same instruments, the both tables were compared with each other. The instrument handovers in Setup 3 are faster for all 3 tables. Although, statistical significance has not been reached for table 2 ( $p = 0.121$ ) and table 3 ( $p = 0.102$ ), a statistical significance in a two-tailed t-test have been reached for table 1 ( $p = 0.004$ ).

Figure 17 - Comparison of the intraoperative instrument handover times of TKA Setup 1 & 3 (left side) and THA Setup 1 & 3 (right side)

The instrument handover times of the new THA Setup 3 were compared to the initial data measured in the initial THA Setup 1 (Figure 17, right). Table 3 and table 4 of Setup 1 were combined for better comparability with the three-table THA Setup 3. The measured handover times of the initial Setup 1 for table 1 were compared with table 1 of Setup 3. Table 2 of Setup 1 was compared with the left-side table 2 of Setup 3. Due to the equivalent instrument usage, table 3 and table 4 of Setup 1 were compared with the right-side table 3 of Setup 3. The instrument handovers in Setup 3 are faster for tables 1 and 3. A statistical significance of Setup 3 in a two-tailed t-test could be shown for table 1 ( $p = 0.0001$ ) and table 3 ( $p = 0.047$ ).

## Incision-to-Begin-of-Closure Time

Secondly, the impact of the improved instrument handover time has an impact on the overall efficiency of the surgical procedure was analyzed. Therefore, the IBCT of Setup 3 was recorded and compared to the initial IBCT performance of the TKA Setup 1 (Figure 18, left). In surgeries performed with Setup 1, the mean IBCT is  $71.1 \pm 20.7$  min. In surgeries performed with the new Setup 3, the mean IBCT was slightly faster with  $70.7 \pm 17.1$  min. Although the variance of procedures performed with Setup 3 is lower and indicates a faster and more efficient surgery, there is no significant difference in the duration of the procedure for TKA surgeries ( $p = 0.94$ ).

The IBCT was also measured for both initial THA setups and subsequently compared to the intraoperatively recorded IBCT of THA Setup 3 (Figure 18, right). The mean IBCT is  $53.2 \pm 14.7$  min for surgeries performed with Setup 1,  $54.5 \pm 22.8$  min for Setup 2 and  $49.7 \pm 12.2$  min for Setup 3. Although the newly designed setup performs on average 3.49 min faster than Setup 1 and 4.77 min faster than Setup 2, a statistical significance was not reached (Setup 1  $p = 0.53$ , Setup 2  $p = 0.50$ ).

Figure 18 - Comparison of IBCT for TKA Setup 1 and 3 (left side) and THA Setup 1, 2 and 3 (right side)

## 3.5 Inter-Setup Evaluation of the Simulation Results

In the last step, the Delmia simulation results of the newly designed THA Setup 3 and TKA Setup 3 were compared with the intraoperatively recorded data to evaluate the accuracy and closeness to the actual intraoperative situation. For this purpose, the instrument handover time was analyzed.

The simulated and real intraoperative instrument handover times (IHT) of TKA Setup 3 and THA Setup 3 are presented in Table 2. The difference between the simulation and real OR IHT are exceptionally small for all tables in TKA Setup 3 and tables 1 and 2 in THA Setup 3. Only table 3 in THA Setup has a higher deviation between simulation and the real OR measurement of 0.66 seconds. Nevertheless, the results indicate high accuracy and closeness of the Delmia simulation to the actual intraoperative situation. This enables a valid evaluation of setup changes by a computer simulation before their implementation in the actual OR environment.

## Discussion

The optimized TKA Setup 3 and THA Setup 3 were permanently implemented in the daily clinical routine at the University of Leipzig Medical Center. In particular, the surgeons and scrub nurses acknowledge the newly designed setups a good operability and improved ergonomics. In a questionnaire study, the OR personnel indicates a high level of satisfaction with the optimized setups [40]. For the TKA setup, the scrub nurses especially like the good view of the operating area and the surgeon, which enables a faster and proactive instrument handover. The surgeons have improved accessibility to the instrument tables and often perform instrument handover without any rotations, which consequently improves the ergonomics of the setup. The same applies to the optimized THA setup. The surgeon does not need to turn or bent the upper body, to grab an instrument. Also, the scrub nurses describe the setup after the position change of the surgeon and the 1<sup>st</sup> assistant as good manageable. The new setups were also analyzed with respect to hygienic considerations and were assessed positively by the Institute of Infection Control and Hospital Hygiene of the University Medical Center Leipzig.

Besides this positive subjective assessment of the optimized setups, an objective assessment has been performed in this study. It could be shown, that the optimized setups perform better in the simulation environment as well as in the intraoperative setting. The instrument handover times, travel paths and the surgery duration could be reduced, and the ergonomic situation, team collaboration, and intraoperative hygiene could be improved by the implementation of the optimized OR setups. Additionally, the simulation results strongly correlate to the intraoperative measured data. Therefore, the developed methodology for the design, simulation, analysis, and evaluation of optimal OR setups has proven its suitability for the intended application. The methodology has been successfully applied to different surgical intervention types and could be adapted to other interventions and surgical disciplines. With the simulation-based methodology, it is possible to analyze different possible setups from different perspectives. This allows a valid assessment of the performance prior to the implementation of untested setups in the intraoperative setting, which could lead to adverse effects. Intraoperative processes are highly variable, complex, intertwined and have a significant impact on each other. Therefore, a change in the intraoperative setting should not be tested ad-hoc without prior considerations and tests.

A drawback of the presented methodology is the high effort for data acquisition and simulation implementation. The study shows that the results are worth the effort due to the improvement of the surgeries' efficiency. The new THA setup is about 4 minutes faster than the initial setups, which could lead to cost savings and improved utilization of available OR capacities [41]. In Germany, the revenue per OR minute is about 16.30€ [42], which could lead to a potential cost saving of about 28.000€ for the averagely performed 400 THA and 170 TKA surgeries per year in the hospital.

## Conclusion

In this work, a methodology was presented for the design, analysis, simulation, and evaluation to determine an optimal OR setup tailored to the specific intervention. For the use case of TKA and THA

surgeries, optimal OR setups were designed, and the simulation results evaluated in the actual intraoperative OR setting. Thereby, the instrument handover time, travel paths, and the surgery duration could be reduced, and the ergonomic situation was improved. Additionally, an inter-setup evaluation was performed to demonstrate the accuracy of the method. The results indicate high accuracy and closeness of the computer simulation to the actual intraoperative situation. This enables a valid evaluation of setup changes before their implementation in the actual OR environment. The presented method proved to be suitable for the presented use case but provides also high flexibility for other optimization objectives concerning the OR layout. Additionally, the method can also be adapted to further interventions and surgical disciplines.

## List Of Abbreviations

A1 *1st assistant*

A2 *2nd assistant*

AN *Anesthesiologist*

AR *Anesthesia room*

CAD *Computer-aided design*

DES *Discrete Event Simulation*

IBCT *Incision-to-begin-of-closure-time*

IHT *Instrument handover time*

MRI *Magnetic Resonance Imaging*

OR *Operating room*

OWAS *Ovako Working Posture Analyzing System*

R1 *Rack 1*

R2 *Rack 2*

SN *Scrub nurse*

ST1 *Supply stock 1*

ST2 *Supply stock 2*

SU *Surgeon*

THA *Total Hip Arthroplasty*

TKA *Total Knee Arthroplasty*

TRM *Total Rotational Movement*

WP1 *Working place 1*

WP2 *Working place 2*

## **Declarations**

*Ethics approval and consent to participate*

Not applicable.

*Consent for publication*

Not applicable.

*Availability of data and material*

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

*Competing interests*

The authors declare that they have no competing interests.

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*Authors' contributions*

J. N. conceived and planned the study design including data acquisition and the simulation experiments. She performed the calculations and data analysis and wrote the manuscript with support from all authors. C. A. carried out the initial intraoperative data acquisition, implemented and performed the simulation experiments and analytic calculations. C. H. carried out the data acquisition of the actual intraoperative OR setup evaluation and analyzed the evaluation data. C. A., D. Z., M. G. and A. R. contributed to the data acquisition and to the clinical interpretation of the data and evaluation results. A. R. and T.N conceived the original idea. T. N. designed and directed the project. All authors discussed the results and contributed to the final manuscript.

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## Tables

Table 1 - Requirements considered during the intraoperative lay outing for optimal OR design

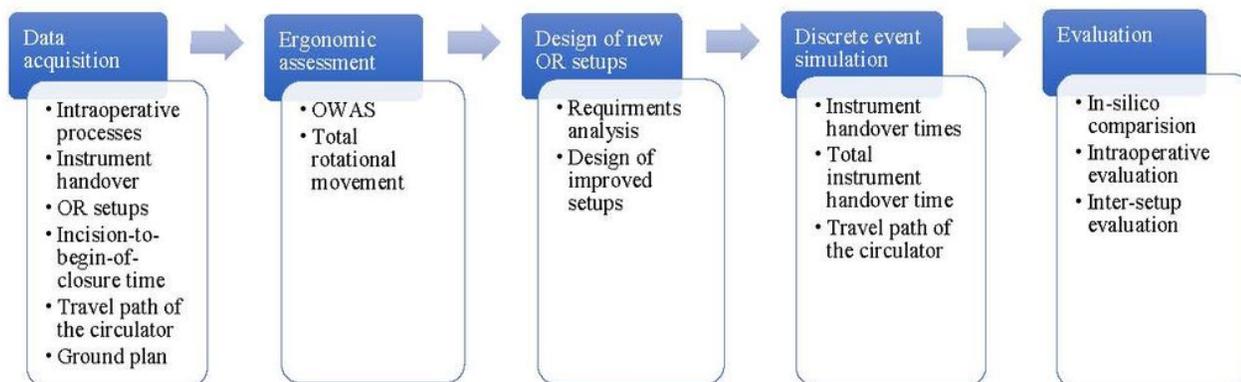
<b><i>Functional requirements</i></b>		
1	Alignment of instrument tables	For the design of optimal OR setups, the positioning of instrument tables should allow the whole OR team, and especially the surgeon, 1 <sup>st</sup> assistant and scrub nurse a direct view on the operating area whenever possible. Hence, the scrub nurse is able to anticipate the surgeons' actual and next needs (e.g. instrument or material handover), which has a positive impact on the process flow of the surgery [12].
2	Relative positioning of instrument tables in proximity to the surgeon	The instrument tables should be positioned in adequate proximity to the surgeon. This shortens the paths for instrument handover between the scrub nurse and the surgeon [12].
<b><i>Spatial requirements</i></b>		
3	Freedom of movement	The space for the OR staff, especially for the surgeon, should be planned generously to ensure unrestricted freedom of movement during surgery. There should also be sufficient space available in the setup if large-sized equipment is used during surgery.
4	Planning of pathways	The pathways to supply stocks, workstations and the sterile area should be as short as possible to minimize the travel path of the circulator during surgery.
5	Sufficient space for medical devices	If large-sized medical devices (e.g. c-arm or a surgical microscope) are needed during surgery, sufficient space should be planned in the setup. When the equipment is not in use, it should be located on the opposite of the surgeon and in proximity to the operating area to enable a fast preparation and set up.
<b><i>Hygienic requirements</i></b>		
6	Positioning of the instrument tables next to or in front of the surgeon	The instrument tables should not be located behind the surgeon. Although in most cases the surgeon is dressed completely in sterile clothing, the back is considered as less sterile due to the clothes closure.

7	Minimizing staff circulation	The pathways of the OR staff, especially the circulator, should no lead too close to the instrument tables. The air flow and unintentional contacts may cause physical and bacteriological effects and increases the risk of instrument and implant contamination.
8	Positioning of the instrument tables in the proximity of the OR table	The instrument tables should be positioned in proximity of the OR table, which is specially protected against pathogens by a sterile area with a stable flow of filtered air.
<b><i>Ergonomic requirements</i></b>		
9	Minimizing the rotational movement of the OR staff	Where possible the instrument tables should be positioned next to or in front of the surgeon and in a U-shape in front of the scrub nurse. This minimizes rotational movement and improves an ergonomic body posture.
10	Avoiding twisted or bent body postures	The height of the OR table and instrument tables should be adapted to the individual needs of the OR personnel [25]. In addition, the operating area and displays in the OR should be seen by the personnel without bending or twisting the head or back.

Table 2 - Comparison of Delmia simulation results and intraoperative measurements of instrument handover times

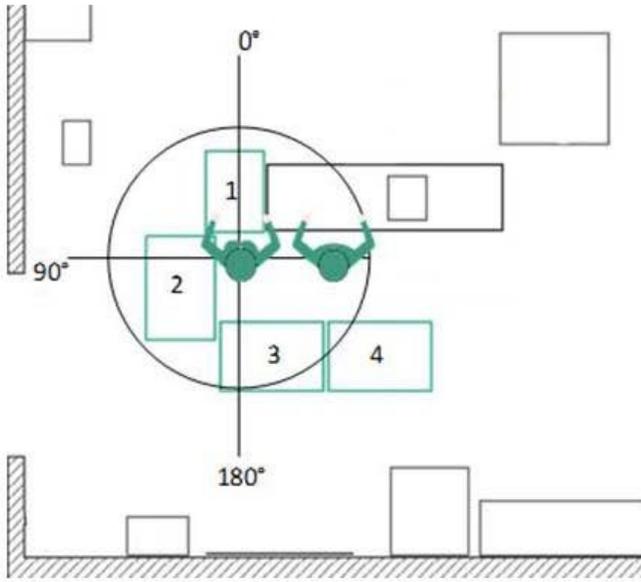
	<i>TKA Setup 3</i>			<i>THA Setup 3</i>		
	IHT Delmia simulation [sec]	IHT intraoperative measurement [sec]	$\Delta$ [sec]	IHT Delmia simulation [sec]	IHT intraoperative measurement [sec]	$\Delta$ [sec]
Table 1	0.70	0.65	0,05	0.79	0.72	0.07
Table 2	1.24	1.14	0,10	1.42	1.44	0.02
Table 3	1.66	1.46	0,20	1.20	1.86	0.66

## Figures



**Figure 1**

Methodology for the objective design and assessment of optimal OR setups



**Table 1**

$$TRM_{T1} = [(0 \cdot 0^\circ) + (2 \cdot 90^\circ) + (2 \cdot 90^\circ)] = 360^\circ$$

**Table 2**

$$TRM_{T2} = [(2 \cdot 90^\circ) + (2 \cdot 90^\circ) + (2 \cdot 90^\circ)] = 540^\circ$$

**Table 3**

$$TRM_{T3a} = [(2 \cdot 180^\circ) + (2 \cdot 90^\circ) + (2 \cdot 90^\circ)] = 720^\circ \text{ or}$$

$$TRM_{T3b} = [(1 \cdot 180^\circ) + (2 \cdot 90^\circ) + (2 \cdot 90^\circ)] = 540^\circ$$

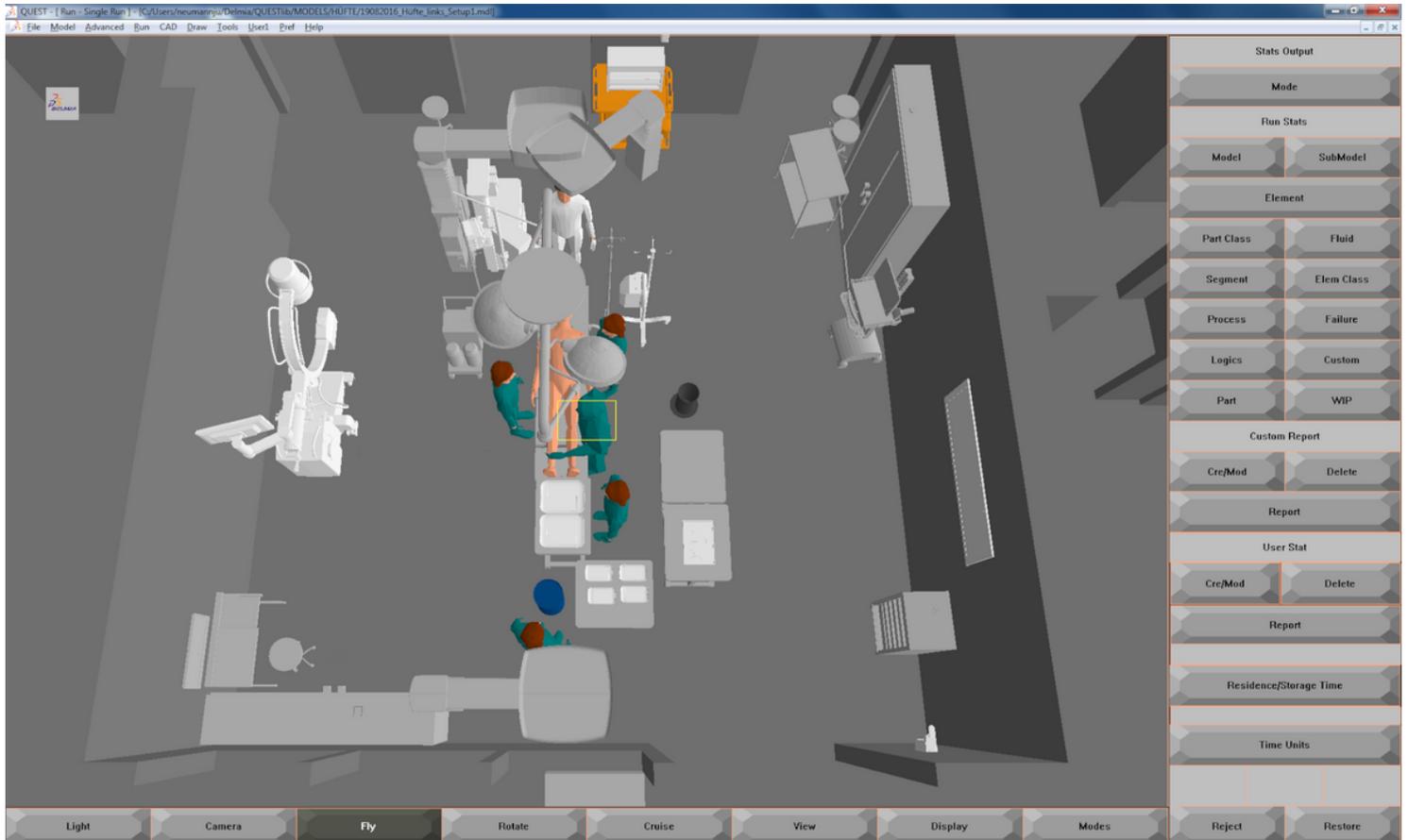
**Table 4**

$$TRM_{T4} = [(1 \cdot 135^\circ) + (1 \cdot 45^\circ + 1 \cdot 90^\circ) + (2 \cdot 90^\circ)] = 450^\circ$$

$$TRM = TRM_{T1} + TRM_{T2} + TRM_{T3b} + TRM_{T4} = 1890^\circ$$

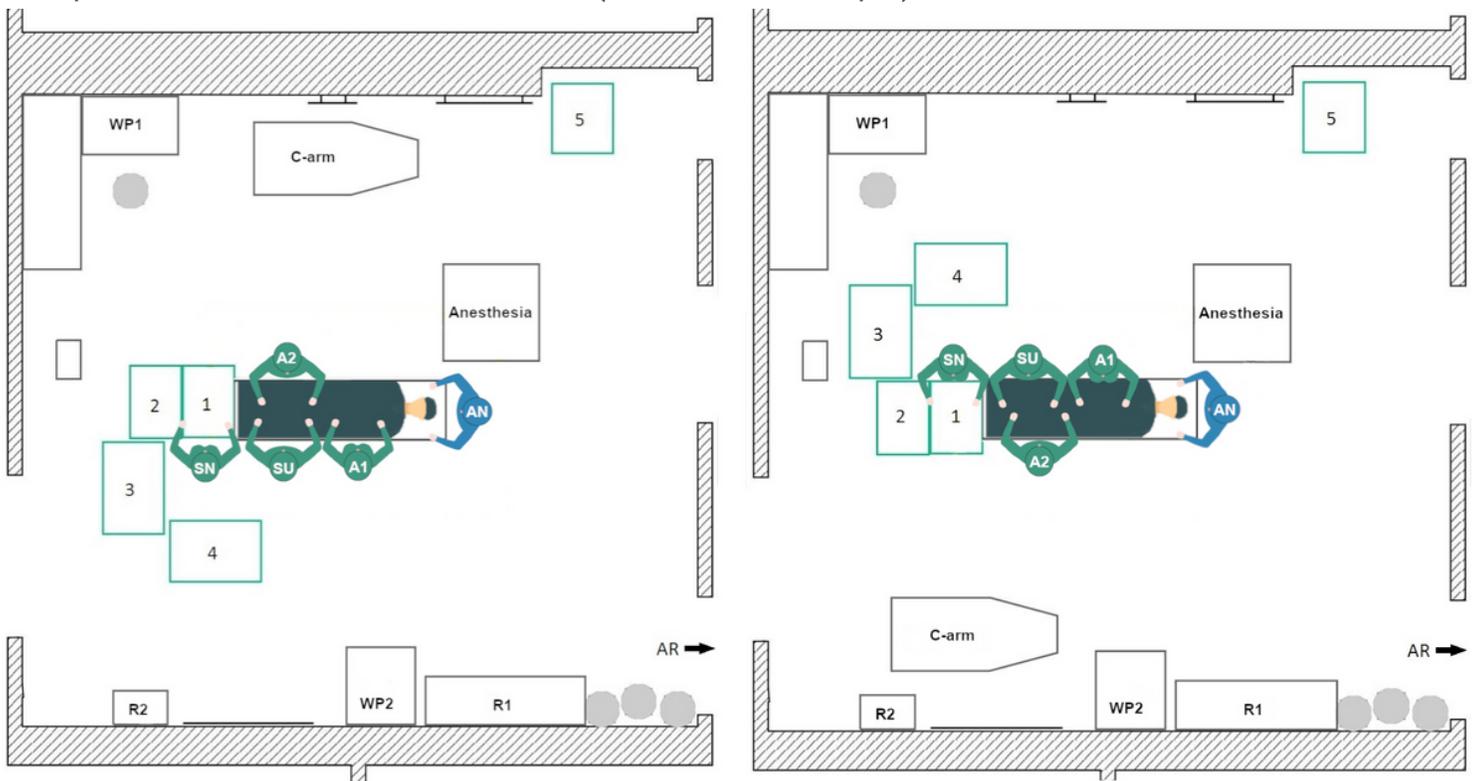
**Figure 2**

Example of the simplified theoretical model to calculate the Total Rotational Movement of an OR setup, including the scrub nurse (left) and surgeon (right)



**Figure 3**

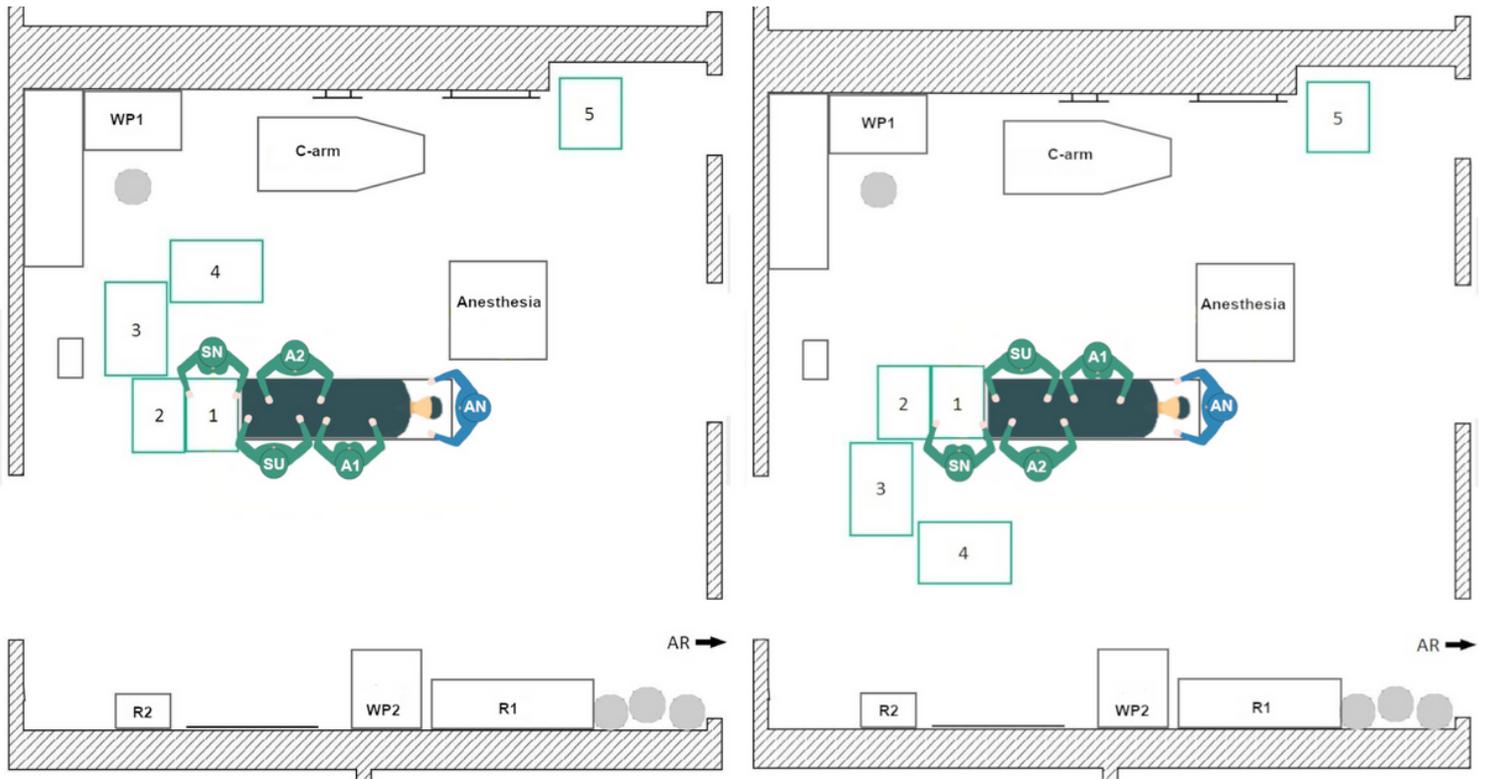
Example of a Delmia 3D simulation model (left-side THA Setup 1)



**Figure 4**

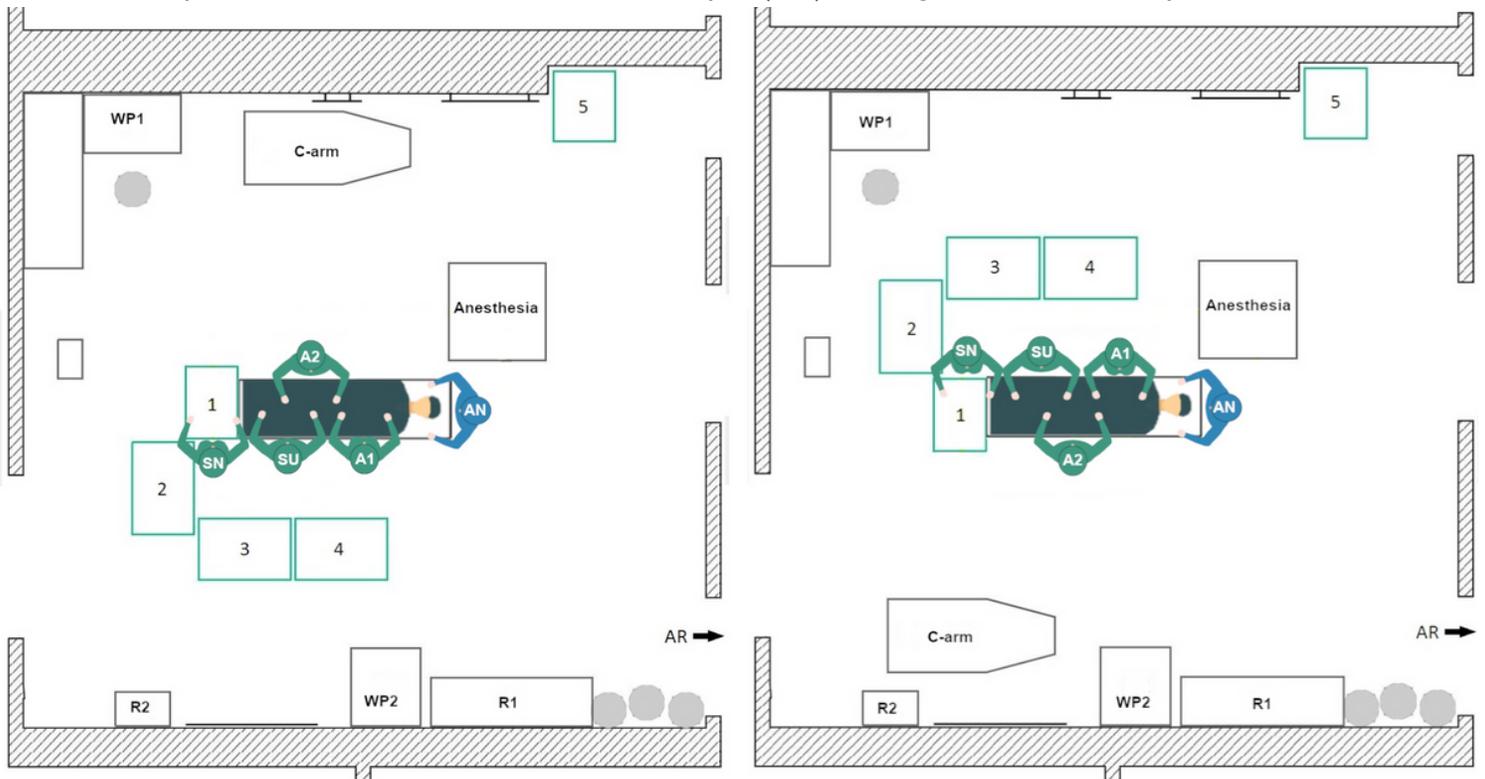
Schematic representation of the left side TKA Setup 1 (left) and right-side TKA Setup 1 (right), (SN – scrub nurse; SU – surgeon; A1, A2 – 1st and 2nd assistant; AN – anesthesiologist; R1,R2 – rack with materials and supplies; WP1, WP2 – working place with displays; AR – anesthesia room)





**Figure 7**

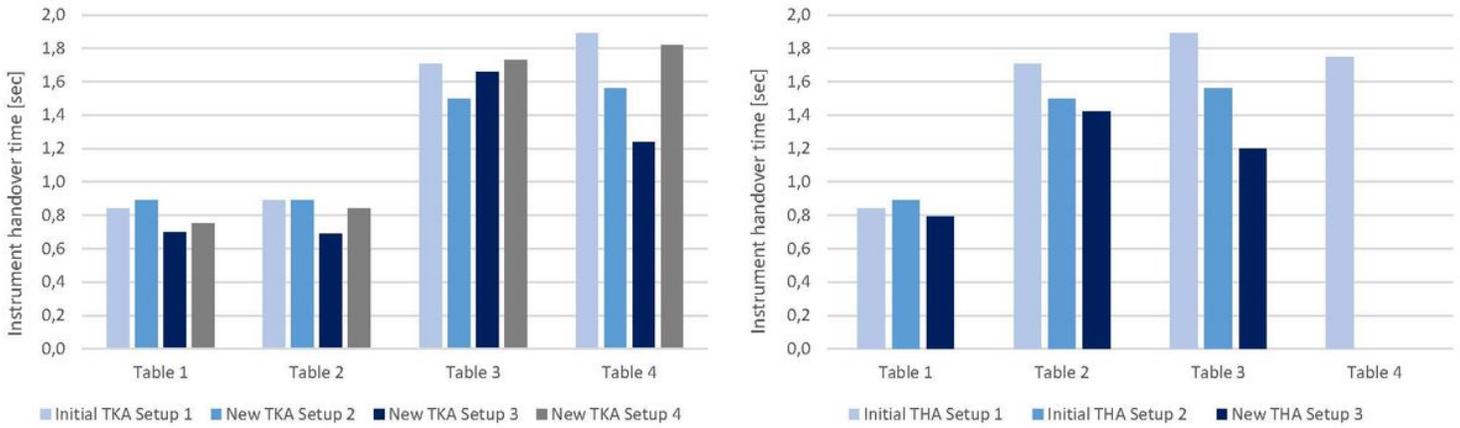
Schematic representation of the left-side TKA Setup 4 (left) and right-side TKA Setup 4



**Figure 8**

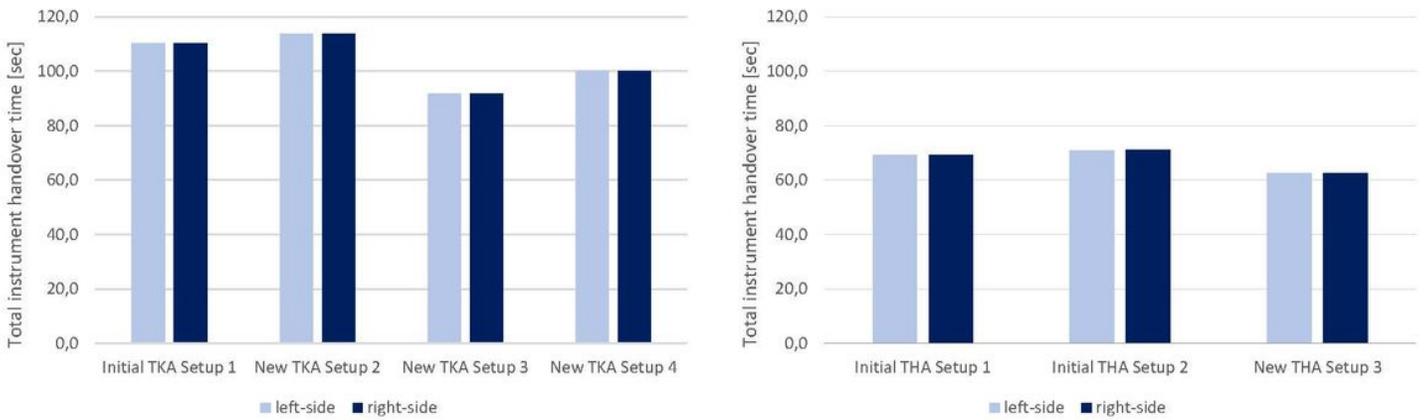
Schematic representation of the left-side THA Setup 1 (left) and right-side THA Setup 1 (right)





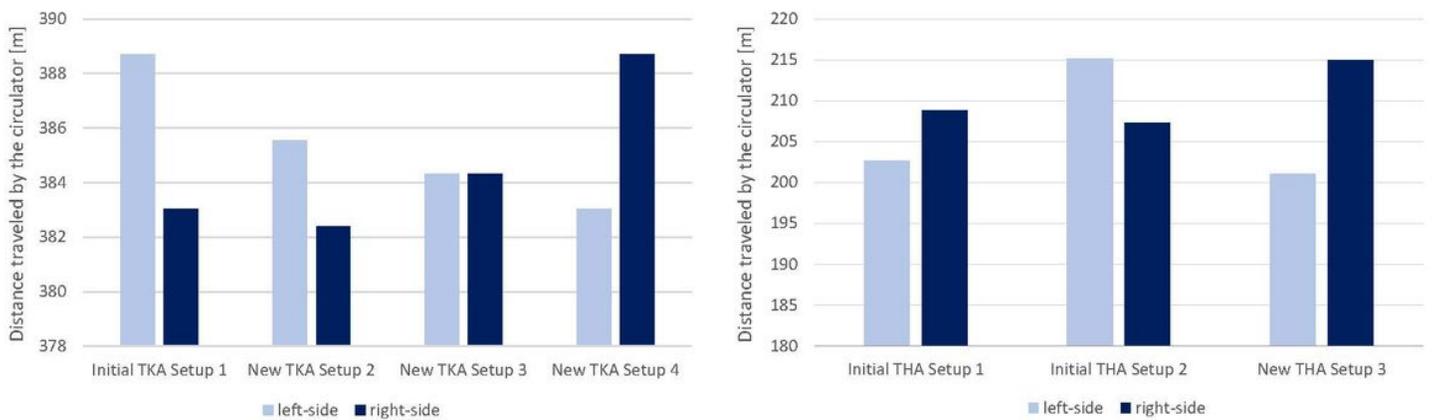
**Figure 11**

Comparison of Delmia simulation results for the instrument handover times of the TKA Setups 1-4 and tables 1-4 (left side) and THA Setups 1-3 and tables 1-4 (right side)



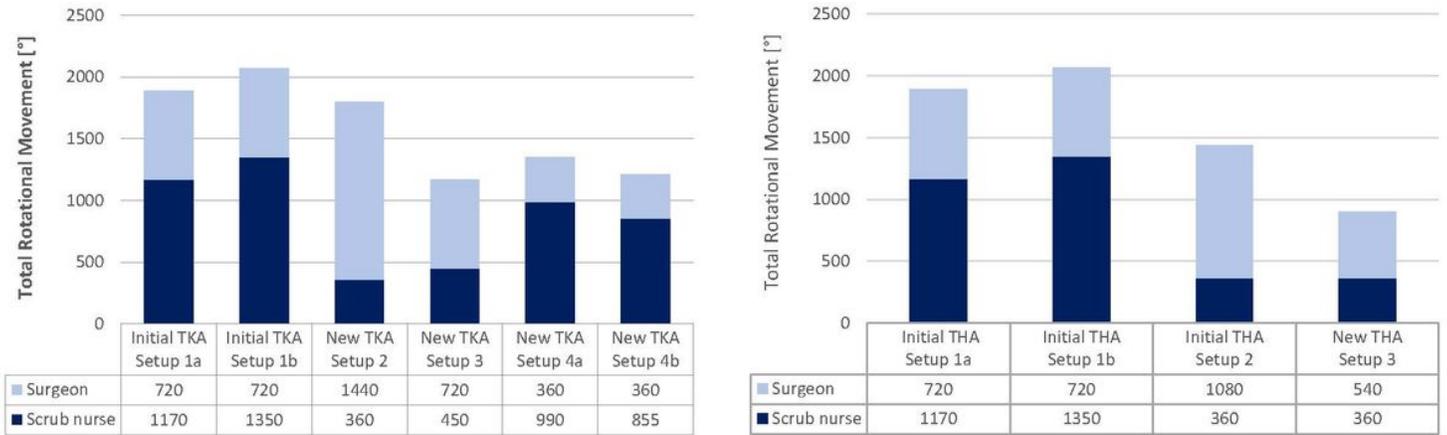
**Figure 12**

Comparison of Delmia simulation results of the total instrument handover time for the TKA Setups 1-4 (left side) and THA Setups 1-3 (right side)



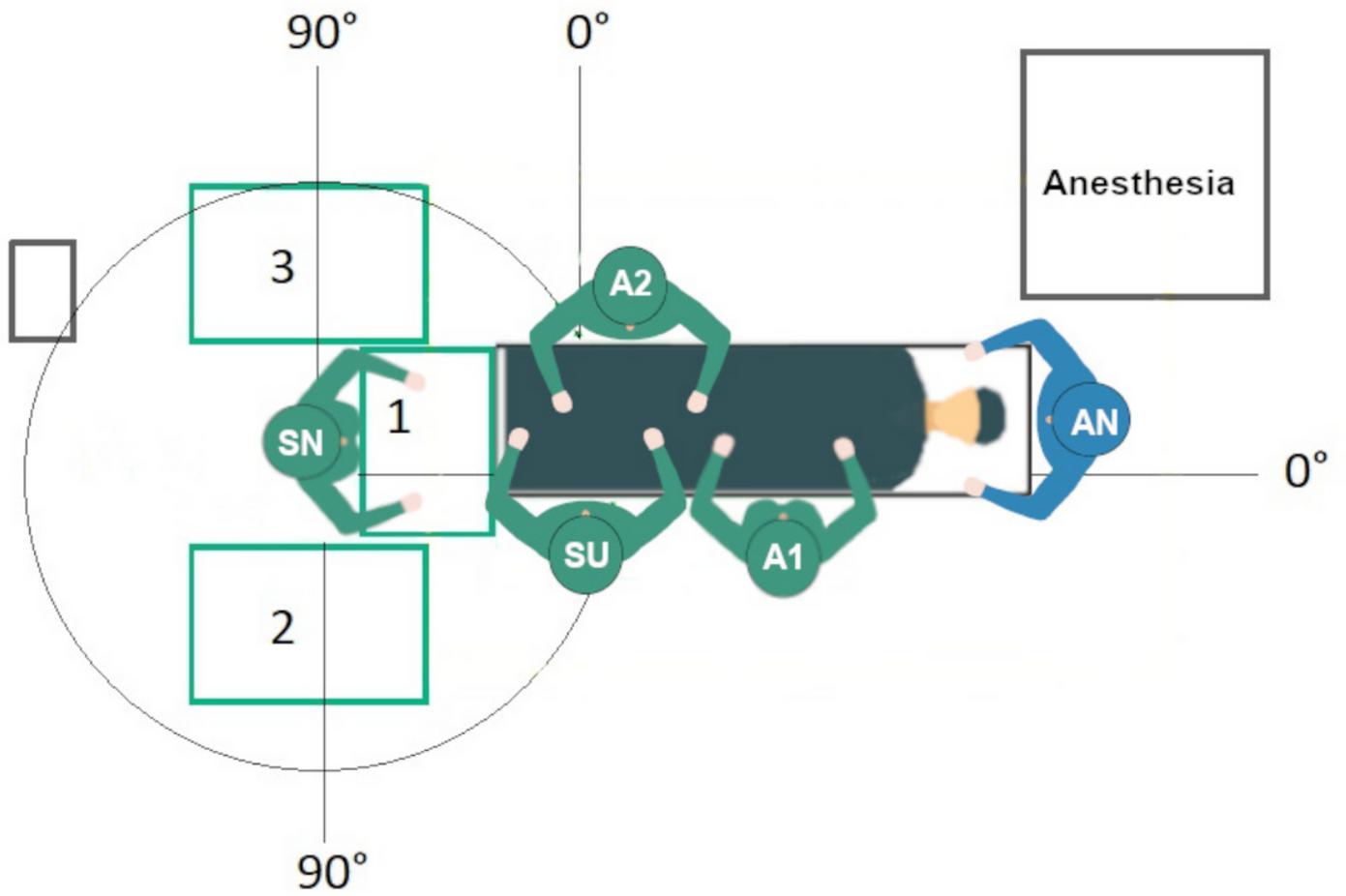
**Figure 13**

Total distance traveled by the circulator during one surgery with TKA Setup 1-4 (left side) and THA Setup 1-3 (right side)



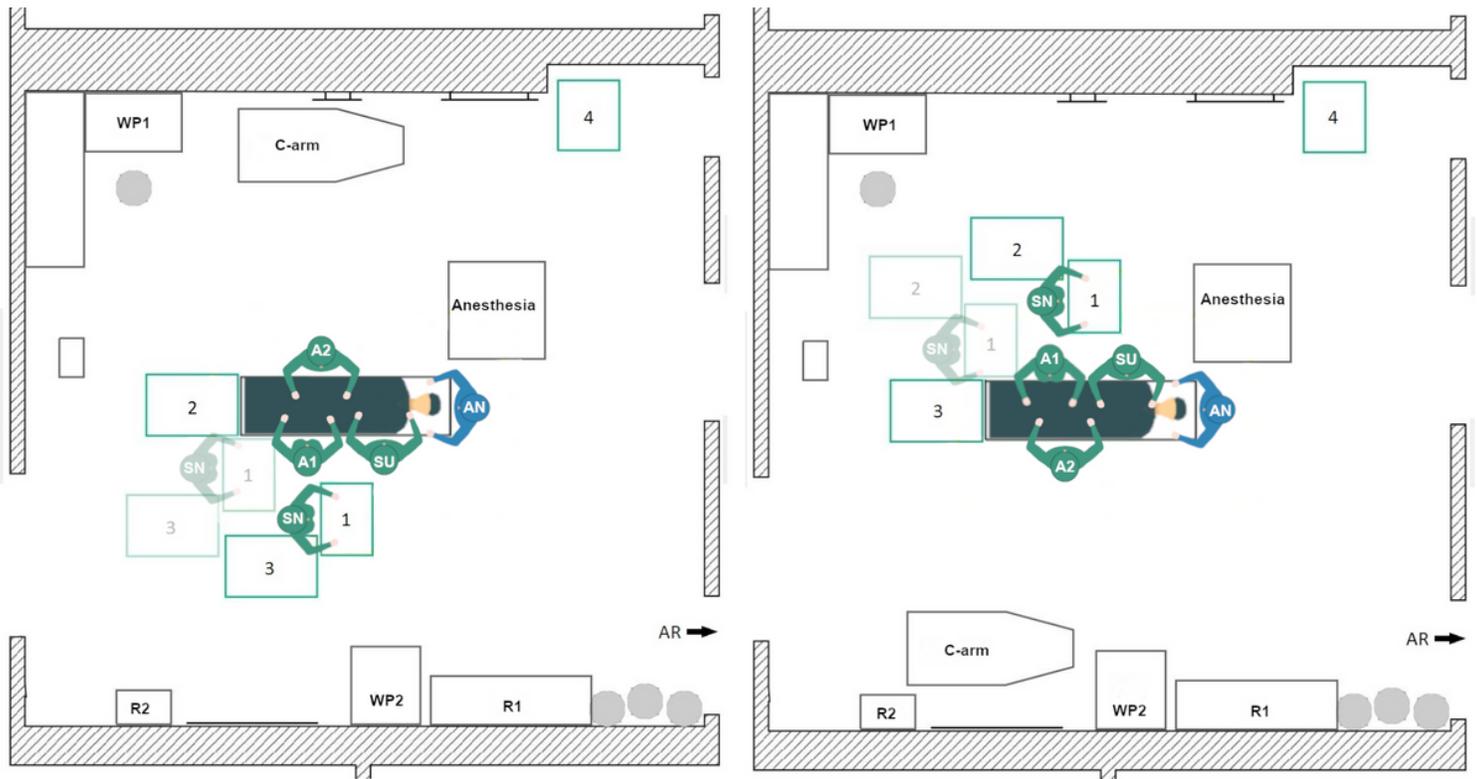
**Figure 14**

Total Rotational Movement for the TKA Setups 1a-4b and THA Setups 1a-3. Setups marked with a are calculated with a rotation to the right side and Setups marked with b are calculated with a rotation to the left-side



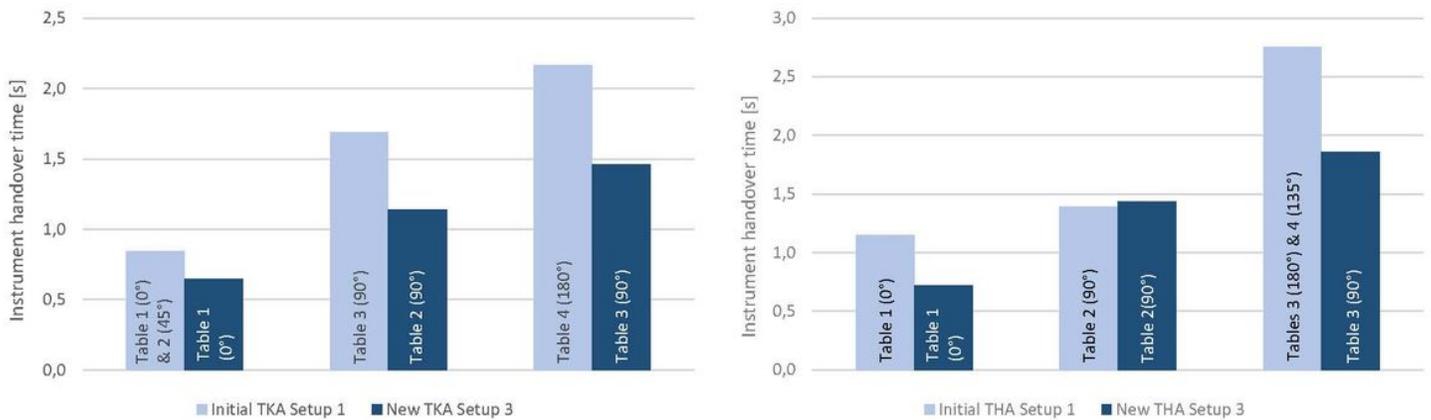
**Figure 15**

Schematic representation of the final TKA Setup 3, which was evaluated in the actual OR setting



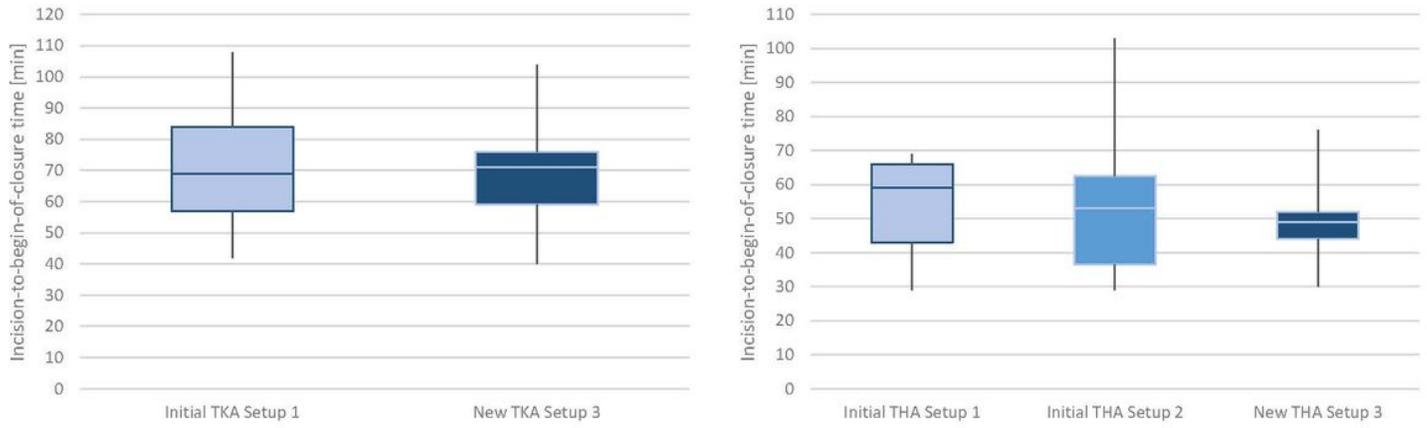
**Figure 16**

Schematic representation of the final left and right-side THA Setup 3 during position change of the surgeon and 1st assistant



**Figure 17**

Comparison of the intraoperative instrument handover times of TKA Setup 1 & 3 (left side) and THA Setup 1 & 3 (right side)



**Figure 18**

Comparison of IBCT for TKA Setup 1 and 3 (left side) and THA Setup 1, 2 and 3 (right side)

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [supplement1.jpg](#)