The surgical lighting problem

‘Manipulation problems with the surgical lighting system during surgical procedures’

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Abstract

Ergonomic problems of surgical lighting systems have been indicated by surgeons; however, the underlying causes are not clear. The aim of this dissertation is to assess the problems in detail, and subsequently clarify the underlying causes.

In the first stage of the research, the observation method was used to quantify the luminaire use during 46 hours of open routine surgical procedures in the field of general surgery. The location of the observation study was the Reinier de Graaf Gasthuis hospital in Delft, which employs the Berchtold Chromophare C series as the surgical lighting system. The results showed that every 7.5 minute a luminaire action takes place, intended to reposition the luminaire. Of these LAs, 74% was performed by surgeons and residents. For 64% of these LAs the surgical tasks of OR-staff were interrupted. Observed difficulties were collision of the luminaire against any object, or that the luminaire was out of reach for the surgeon in a sitting posture. The primary difficulty appeared in the kinetic relation during the SLS and user interaction, as manoeuvrability of the luminaire was cumbersome and in some situations the system was immovable. These problems primarily occur during the repositioning of the luminaire 2 dimensional plane of the pendant arms.

In the second research stage a valid simulation model of the surgical lighting system was constructed in MSC Adams software to allow virtual experiments to analyse the system mechanics. The model showed that the required force during luminaire usage depends on the location of the luminaire its work field and are on average higher than ergonomically acceptable. Primary cause of this difficulty with the current systems is the two pendant arms construction as the highest forces were found when the luminaire was directly below the ceiling suspension or in the peripheral region of the work field. In those regions the pendant arms are either in parallel or serial alignment. The force spectrum for luminaire use showed a diffuse image, ranging from 14 Newton till unlimited quantities when the system is unmovable. The average required force is 136 Newton in the region where the observed luminaire use was primarily undertaken. In addition, the software engineering model which was constructed in this study is applicable as a test procedure to analyse surgical lighting systems.

As a result, this dissertation stated novel insights into the OR lighting problem during open routine surgical procedures in the field of general surgery. And it presented a valid simulation model of a surgical lighting system Berchtold Chromophare C series. The protocol for the model construction can be user to analyse surgical lighting system of different brands using engineering software simulation. Furthermore, this dissertation presented a direction for future research and an improved user system interaction of the luminaire during surgical procedures.

Acknowledgement

This research project would not have been possible without the support of many people. I wish to express gratitude to my supervisors Arjan Knulst (TU Delft) and Jenny Dankelman (TU Delft), who were abundantly helpful and offered invaluable assistance, support and guidance.

And a special thanks goes to the staff of the Reinier de Graaf hospital, in particular Laurent Stassen, for their warm welcome and cooperation during the observation of the surgical procedures. Also Chris Verheul (SayField International) and Arend Schwab (TU Delft) for their knowledge and time to help me with the software simulation of a surgical lighting system.

I cannot forget to thank my dear friend Floris Lewis who was always there through the duration of my study. Last but definitely not least, I wish to express my sincere appreciation to my beloved Mariet Feenstra for her understanding, support & love during the struggle of my graduation.

Preface

This master thesis is the written work of my graduation project at the faculty of Mechanical, Maritime and Materials Engineering at Delft University of Technology. My interest in physiological systems was the reason to step into the section of Medical Instruments at the department of BioMechanical Engineering in Delft. The work presented here is the result of research done in the field of Minimally Invasive Surgery & Interventional Techniques, which was directed at the ergonomic problems indicated by surgeons of surgical lighting systems during surgery. As such the work is part TU Delft project *LIFE OR*; Lighting & Instrumentation Flexible & Ergonomic - Operating Room; aimed at improving lighting and instrumentation in operating rooms to obtain a flexible and ergonomic working environment for both surgeons and nursing staff.

The volume entails three parts: Two scientific papers and a research report. Each part is composed as an independent entity, but the papers are the abbreviation of the research and the research report functions as a complementing appendix:

A. The paper entitled *'Indicating shortcomings in surgical lighting systems'*, which entails the observation study of my research. As a co-author, the presented paper is the original article published in the journal of Minimally invasive therapy & allied technologies (MITAT), in November 2010;

B. The paper entitled *'Simulation model of a surgical lighting system'*, which entails the performed work by a self constructed simulation model of the surgical lighting system;

C. The research report, as an appendix for the papers, states the application of the two research methods in greater details, including the research context, rationale and clinical setting of the research problem.

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Part A

Paper *‘Indicating Shortcomings in Surgical Lighting Systems’*

ORIGINAL ARTICLE

Indicating Shortcomings in surgical lighting systems

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Keywords

Ergonomics, equipment, operating room technology, surgical lighting, usability

Abstract

Ergonomic problems of surgical lighting systems have been indicated by surgeons; however, the underlying causes are not clear. The aim of this study is to assess the problems in detail. Luminaire use during 46 hours of surgery was observed and quantified. Furthermore, a questionnaire on perceived illumination of and usability problems with surgical luminaires was issued among OR-staff in 13 hospitals. The results showed that every 7.5 minute a luminaire action (LA) takes place, intended to reposition the luminaire. Of these LAs, 74% was performed by surgeons and residents. For 64% of these LAs the surgical tasks of OR-staff were interrupted. The amount of LAs to obtain a well-lit wound, the illumination level, shadows, and the illumination of deep wounds were most frequently indicated lighting aspects needing improvement. Different kinematic aspects of the pendant system of the lights that influence usability were also mentioned: high forces for repositioning, ease of focusing and aiming, ease of moving, collisions of the luminaire, entangling of pendant arms, and manoeuvrability. Based on these results conclusions regarding to improvement of surgical lighting systems are formulated. Focus for improvements should be on minimizing the need for repositioning the luminaire, and on minimizing the effort for repositioning.

Introduction

For many years, illumination of wounds during surgery has been done by surgical luminaires. Such a surgical lighting system (SLS) basically consists of a large, heavy luminaire suspended from the wall or ceiling by a two-arm pendant system. The luminaire has been designed such that high-intensity light is supplied to the wound while minimizing shadows of heads and hands of the surgical team. The pendant system has been designed to allow great flexibility in positioning of the luminaire and to stabilize the position of the luminaire in a certain position.

Although the fundamental design of the SLS has not been changed for years, surgeons still complain about their SLSs. Ergonomic shortcomings of several aspects in operating rooms, including surgical lighting have been indicated by different authors [1-8]. A German and an Australian study both have indicated a need for ergonomic improvements of the lighting system [7, 8]. Complaints varied from colliding pendant arms to lights banging against heads and from insufficient illumination to one-handed adjustments of the lights being impossible. The underlying causes of these problems and how often and in what situations these problems occur were not studied. For improvement of SLSs, more detailed information on shortcomings and problems of SLSs is needed.

The aim of this study was to assess the shortcomings of SLSs in more detail and indicate areas of interest for improvements in the design of SLSs. An observational study in the operating room (OR) during various types of surgery was used to detect and quantify problems of perioperative luminaire usage. An online questionnaire was used to extend the observed findings by the user experience of both surgeons and assistants to different SLSs and to different Dutch hospitals. The outcome of the study pinpoints areas of interest for improving SLSs.

Methods

Observational study
The study was carried out in the Reinier de Graaf Hospital in Delft, a large non-university teaching hospital. Observations were done in two ORs having the same SLS consisting of a large main luminaire (Berchtold Chromophare C950) and a small auxiliary luminaire (Berchtold Chromophare D530 plus).

Both luminaires have an adjustable focus and illumination level, and 5 degrees of freedom (3 translations of the luminaire, 2 rotations of the luminaire and 1 rotation of the complete SLS around its central ceiling mount during which system loses one the translational direction).

In the study the use of the OR luminaires during 46 hours of surgery (14 procedures) was observed. The surgical procedures were selected with the surgeons for both their routine nature and likeliness for luminaire actions (LAs). Some procedures included multiple wound locations at different locations of the body, some had large wound areas and others had narrow and deep wounds. The selected procedures were: 6 gastrointestinal, 2 vascular, 3 breast, and 2 thyroid gland surgical procedures.

During surgery all SLS-related actions of any OR staff were recorded, initially only on a predefined fill-out spreadsheet, and during the last 10 procedures also by a video camera. The video camera captured only the SLS and OR staff interacting with the SLS, the patient remained out of the camera's sight. OR staff was asked to explain the reason for the LA, but only if the clinical situation allowed this communication to the observer.

Afterwards, the video recordings were analyzed manually and the results were added to the spreadsheet. The complete spreadsheet listed:

- The function of the luminaire operator (LO) performing the LA: either being surgeon, resident, assisting nurse, or circulating nurse;
- Whether the LO was actually performing surgical tasks at the moment of LA;
- The type of the LA: either translating or rotating the luminaire, adapting the illumination level, or adapting the focus of the light;
- The duration of the LA, defined from the moment that the operator starts looking for the luminaire to begin interaction until the LO ends his interaction by continuing his original task;
- Whether relocations of the luminaire did take place along the shortest route in 3D space;
- Whether the relocation was one- or two handed;
- The phase of surgery: three phases were determined:
  1. Initializing: the team is ready to start, but no incision is made yet,
  2. Surgery:
     a. Opening: from first incision to the placement of retractors,
     b. Surgical tasks: from placement of retractors until removal of the retractors,
     c. Closing: from removal of the retractors until the last stitch,
  3. Finalizing: the wound is closed, but still some actions to the patient are being performed;
- Any additional comments on the LA.

Questionnaire

To extend our findings from the observational study to other hospitals an online questionnaire was formulated. Thirteen hospitals were included, being university and non-university teaching hospitals. Each questionnaire was tailored to the SLSs installed in those hospitals. The questionnaires were spread in each hospital among surgeons, residents, and OR nurses by surgeons that supported the study.

The questionnaire consisted of two parts:

1. A series of questions to profile the participant, and to let them indicate procedures where lighting is perceived as cumbersome;
2. Items in which the participant had to indicate their most used SLS from a listing of pictures and whether or not different aspects for lighting and usability of this SLS had to be improved.

The results of the questionnaire were exported to MS Excel for analysis.

Results

Observational study
During the observed 46 hours of surgery, in total 364 LAs were noticed, resulting in an average of one LA every 7.5 minutes. All those LAs were identified as repositioning actions of the luminaire. The light beam's focus or the illumination levels were never adapted during the observation period. The dominant reason (97%) for the LAs was a change of the surgeon's area of interest where optimal vision was needed.

Figure 1 shows which OR staff member performed the LAs during surgery as percentage of the total number of LAs. The surgeons performed 45% of all observed LAs, and in 97% of those LAs these were interrupting their surgical tasks to do the LA. Residents took 25% of the LAs, during which they were interrupting their surgical tasks in 73% of the cases. Assisting nurses took 22% of the LAs (0% interrupting surgical tasks) and circulating nurses took 7% of the LAs (0% interrupting surgical tasks). In total, 64% of all LAs surgical tasks were interrupted for repositioning the light.

Figure 1 - Luminaire actions (LA) performed by OR-staff members. In many LA the staff member was simultaneously performing surgical tasks (ST) that were interrupted for the LA.

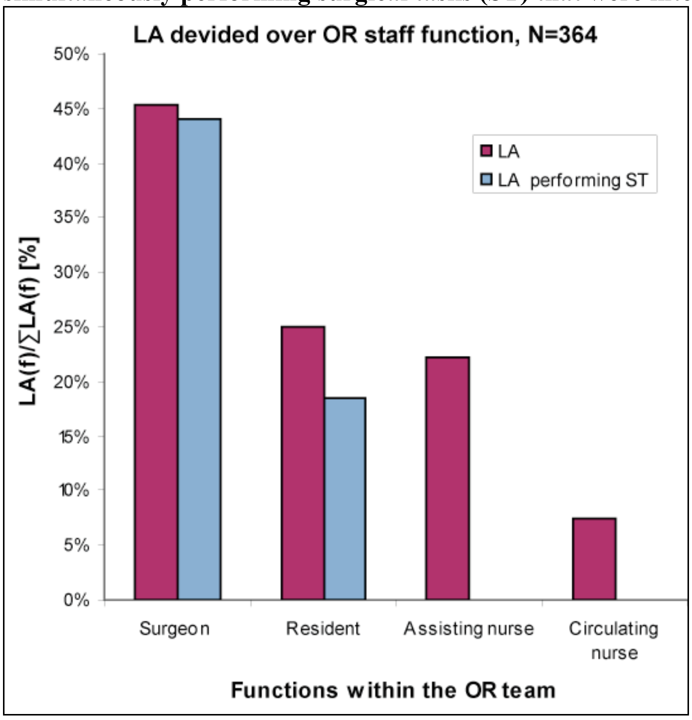
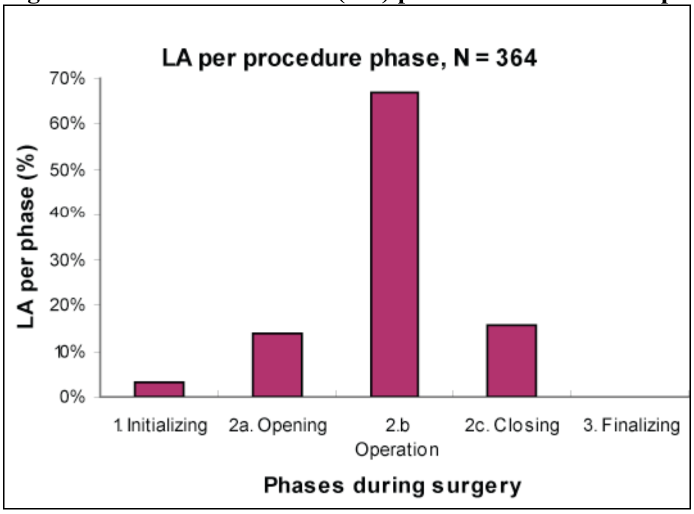


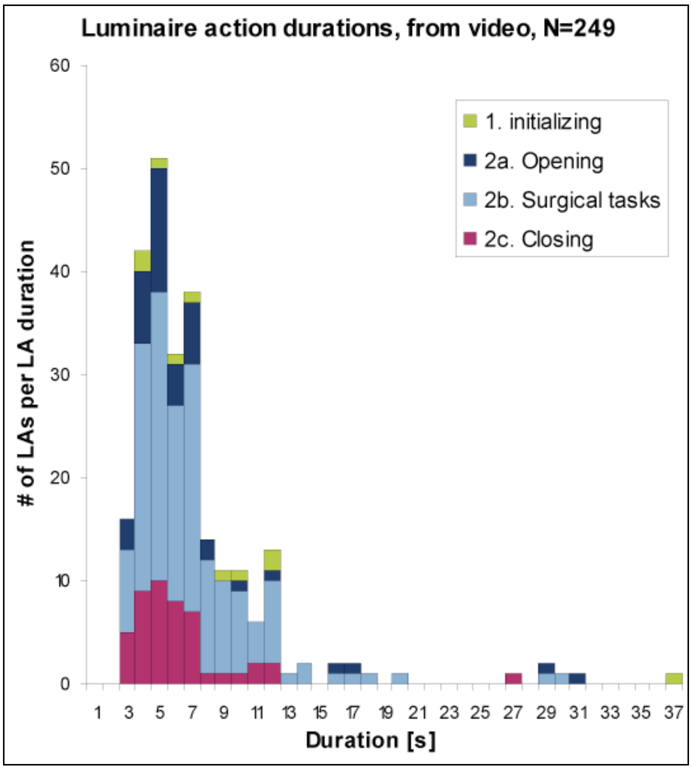
Figure 2 displays in what phases of surgery the LAs occurred. Most LAs (67%) took place during phase 2b, where actual surgery in the wound was being performed. During the opening and closing of the wound 30% of the LAs were done, mainly because the knife or the needle driver were followed with the light pattern when progressing along the line of incision.

Figure 2 - Luminaire actions (LA) performed in different phases of the surgical procedure.



The LAs that were recorded on video (249 LAs) could be more extensively analyzed afterwards. Figure 3 shows a histogram of the duration of the LAs, stacked by surgical phase. Most LAs (78%) took less than 8 seconds to complete the action. The remaining 22% LAs took longer to complete because of complications during the LA.

Figure 3 – stacked Histogram in which the duration of every single luminaire action (LA) that was recorded on video is distributed over 1-second intervals.



The median LA durations - overall and per phase of surgery - are given in Fig. 4. The outliers indicate the most problematic adaptations of the SLS. Clearly, most complications occurred during surgery phase's 2a-2c, where they have the highest impact on distraction of the surgical team.

Figure 4 - Boxplot displaying Luminaire action (LA) durations during surgery, analyzed for the complete dataset (Overall) and per phase of surgery (phase 1 to 2c).

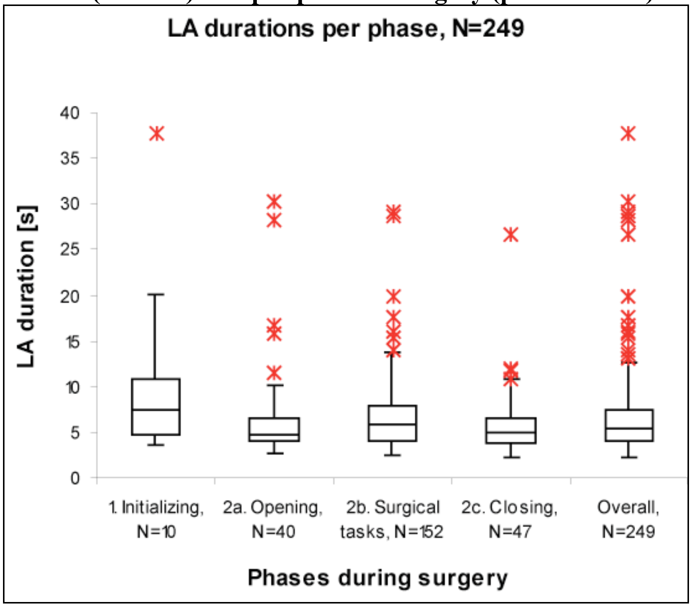
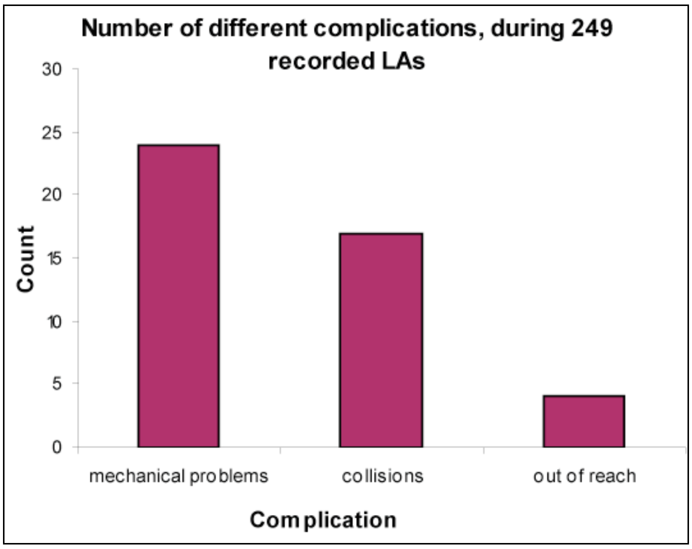


Figure 5 depicts the observed complications:

1. Mechanical problems (24 events): These problems included high forces, requiring two-handed adaptations; locking of the pendant system, in which moving it by operating the sterile handle is completely impossible, in some cases the circulating nurse had to help on the repositioning.
2. Collisions of the luminaire against any object (17 events): when moving the luminaire around, it bumps into other lights, against heads of OR-staff, against its own ceiling mount, and against IV-poles.
3. Out of reach: Surgeon had to stand up (4 events): from a sitting posture the lights were hard to reach or control.

Figure 5 - Different type of complications in luminaire use that were observed during performing luminaire actions.



If such complications occurred, they caused the median duration of the LAs to double (Fig. 6).

Figure 6 - The effect of complications (Fig. 5) during LA on LA duration.

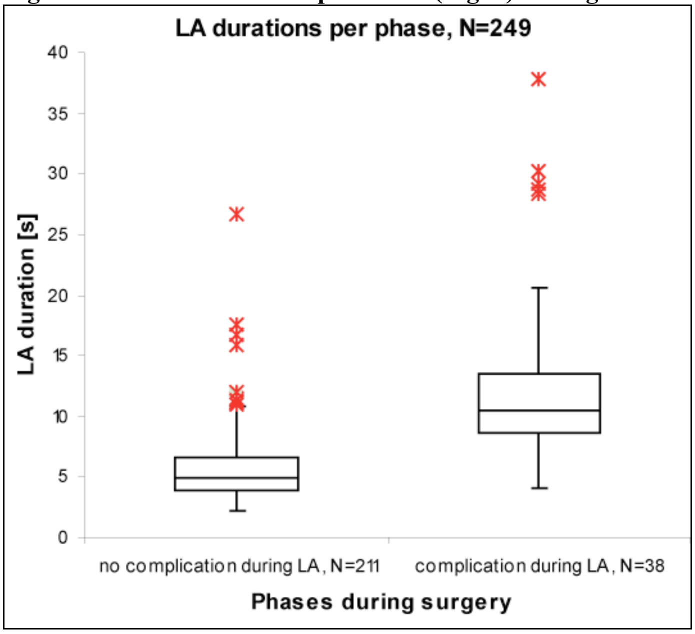
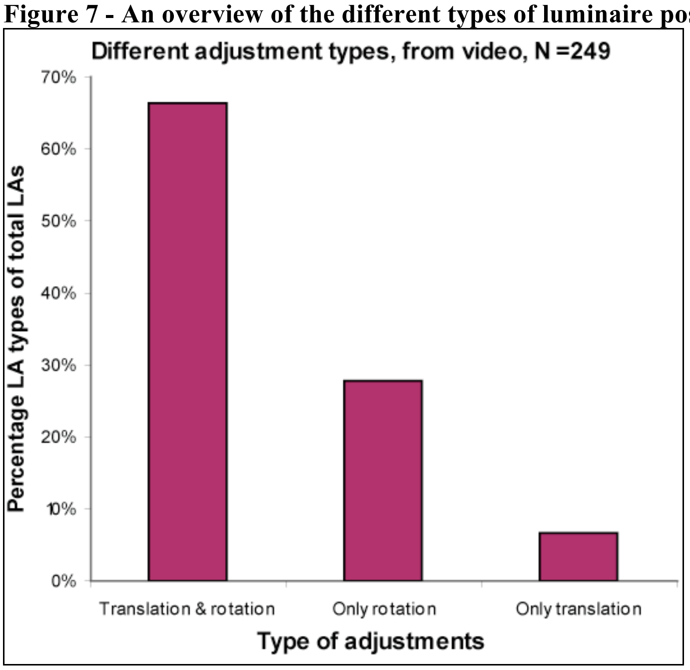


Figure 7 shows whether the LA was a pure translational movement of the luminaire, or a pure rotational movement, or a combination of these. Almost 30% were pure rotations of the luminaire, consisting of slight adjustments of the location of the light pattern on the wound. Most LAs (66%) were combinations of translations and rotations, either because of larger changes of the light pattern location, or because of change of the angle of the light beam.

The video analysis showed that in 56% of all LAs the luminaire was not repositioned from any point A to B along the shortest possible path, but along an alternative trajectory. LAs where the shortest path was followed took about 66% the median duration of a non-shortest path LA (4.5 vs. 6.8 s).

Figure 7 - An overview of the different types of luminaire positioning actions.



Questionnaire

Part 1. The questionnaire was completed by 98 OR staff members from 12 hospitals, of whom 43 (43%) were surgeons, 16 (16%) were residents, and 40 (40%) were OR nurses. Most participants were female (57%) and 43% were male. Of the surgeons, 51% were general surgeons, 16% vascular surgeons, and the remaining 33% were either orthopedic, trauma, thoracic, or gynaecological surgeons. Most participants (91%) were working in ORs equipped with 2 luminaires, and two groups of each 4% were working with 1 or 3 luminaires. Many of the surgeons (88%) indicated that they experienced problematic lighting during surgery. The top 4 examples of procedures that have problematic lighting that were mentioned are: transthoracic surgery (23%), (deep) pelvic surgery (21%), rectal surgery (15%), and deep abdominal surgery (15%). In general, the problematic types of surgery seem to have a deep wound with a narrow entrance to the cavity.

Part 2. Figure 8 shows where OR staff saw needs for improvement on 9 light-related aspects of SLSs. The results for each aspect of lighting are split for suggestions of surgeons, residents, and OR-nurses. The mostly indicated areas of attention for improvements –and thus the most perceived problems- were: the illumination of deep wounds, the frequency of repositioning the light to keep proper illumination, reduction of shadows, and the illumination level of the light beam.

Figure 8 - Responses of surgeons (N=43), residents (N=16), and OR-nurses (N=39) on the question if improvement was needed for 9 different aspects of lighting.

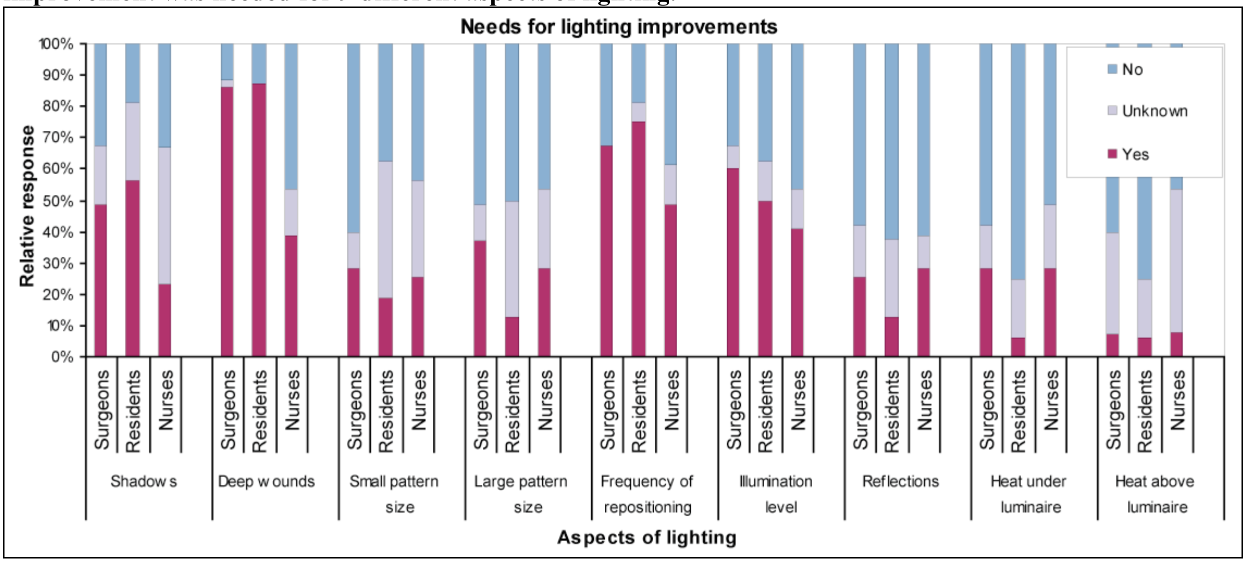
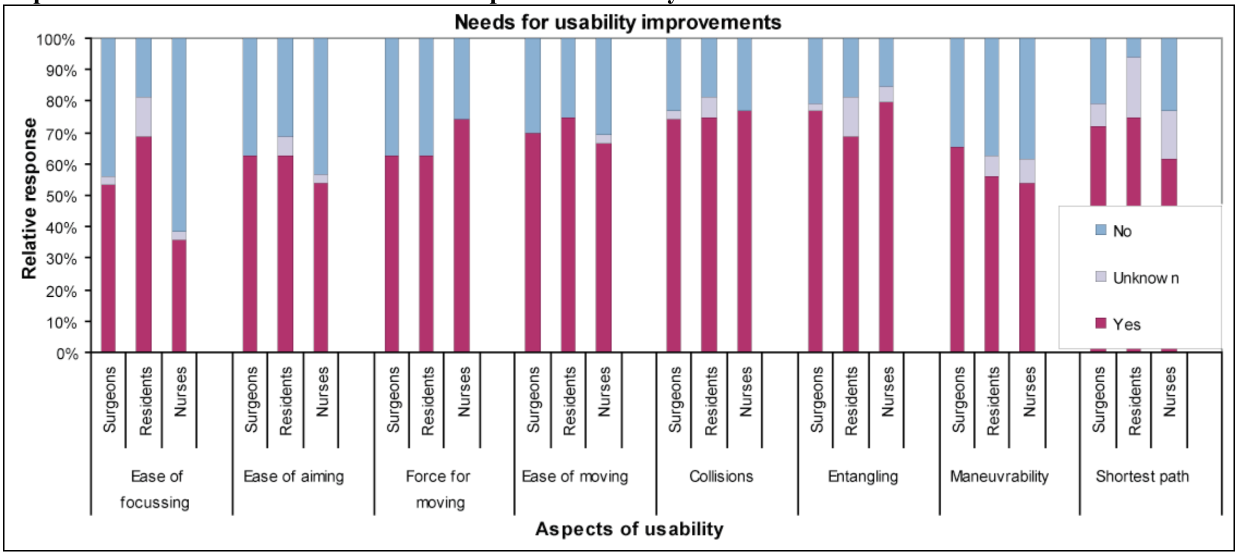


Figure 9 displays where OR staff indicated room for improvement on 8 usability-related aspects of SLSs. The results for each aspect of usability were subdivided in suggestions of surgeons, residents, and OR-nurses. Compared to Fig. 8, the general need for improvements on usability seem to be higher than for lighting. Moreover, the indicated aspects for improvement were not limited to a few items, but covered almost all questioned aspects. These results confirm the observed problems in the OR.

Figure 9 - Responses of surgeons (N=43), residents (N=16), and OR-nurses (N=39) on the question if improvement was needed for 8 different aspects of usability.



Discussion

This study shows that the need for repositioning the luminaire during surgery is high, and that repositioning is cumbersome. The focus of improving surgical lighting systems should be on minimizing the need for repositioning the luminaire, and on minimizing the forces required for such actions.

The aim of this study was to assess shortcomings of surgical lighting systems (SLSs) and indicate areas of interest for design improvements of SLSs, by observing SLS usage during 46 hours of surgery and by a questionnaire filled out by 98 OR-staff members. It was shown that luminaire actions (LAs) occur frequently, every 7.5 minutes. Furthermore, it was shown that those LAs were dominantly done by the surgeon, interrupting the surgical tasks. The reason for these LAs was to re-establish good lighting at changing working areas within wounds, especially in large wounds, in small deep wounds, and in case of multiple wounds. Different mechanical shortcomings of the SLSs caused more than one fifth of the LAs to be cumbersome to perform and to take more time to complete. High operating forces and immobility of the luminaire in certain positions seemed to cause most of the LA problems, together with the expected risk of collision. These observations were also perceived as problematic by OR staff, as shown by the questionnaire.

The validity of our observational findings was extended by using a questionnaire in different university and non-university teaching hospitals to check the observed problems of SLSs. The numbers of hospitals, staff members and different surgical disciplines that were included in this questionnaire were limited. Due to this limitation some problems that are specific for certain surgical disciplines might be overlooked. However, the general problems with SLS use - like lighting deep wounds, shadows, and mechanical issues - are likely to be valid in any surgery as the basic task and setup of the SLS is identical, although the frequency of problem occurrence might be different because of differences in the surgical situation.

Most LAs were performed by surgeons and residents, while they were performing surgical tasks. This is logic, as only they can judge when lighting is insufficiently directed or what improvement in illumination can be expected when the luminaire is repositioned. Therefore, it is wise that they are in command of the lighting system. However, it is undesirable that their attention is drawn away from surgery frequently, for an unnecessary long period of time or too intensively. Especially in crucial situations inadequate lighting or a cumbersome repositioning process to obtain a well-lit situation was reported to create potential hazards [8].

A sound surgical lighting solution will provide always good illumination at a wide range of locations simultaneously, thus minimizing the need for and effect of luminaire repositioning. As small-entrance deep wounds were reported to be difficult to illuminate, the development of tailored lighting solutions might be advisable for these cases. Surgical headlights might improve lighting in these cases, but they have drawbacks in terms of comfort, mobility, and user-friendliness. In such way, the need for frequent luminaire repositioning will be reduced. A further experimental study with wound models – especially the hard-to-illuminate wounds - and different illumination concepts, including the use of surgical headlights, will give better insights on this matter.

Meanwhile, when the need for luminaire repositioning arises, the surgeon should be able to perform this task with minimal effort and by paying minimal attention to this secondary task. An important issue is the high forces that are required to reposition the luminaire, and that are to be exerted in -ergonomically- a challenging posture: above the head. These forces seem to vary with the position of the luminaire relative to its ceiling mount. Close to this ceiling mount the required operating forces will increase enormously, and cause even an immovable luminaire, presumably because of a severe reduction of the moment arm whilst friction moments in the pendant system still need to be overcome. Also the large number of repositioning via non-shortest paths can be explained by the large forces in some areas of the workspace. A model is currently being developed to estimate the contribution of different mechanical parameters to the required operating force in different luminaire positions. With the help of such a model an improved low-operating force pendant system can be developed.

Attention should also be paid to the risk of collisions and entanglement of the luminaire or pendant with heads, other luminaires, or pendant arms. Especially in ORs with many pendant arms for various pieces of equipment these collisions and entanglements are problematic. Solving this problem is not straightforward. A lighting system without pendants would tackle this aspect, but would induce reduced mobility and flexibility of the system, causing many situations hard to illuminate. A robotic, intelligent pendant system on the other hand, could avoid collisions when repositioning the luminaire; however, this increases complexity and costs. Further analysis on collision prevention is required.

Conclusion

In conclusion, this study pinpointed illumination and usability shortcomings of present surgical lighting systems. The quintessence of improving surgical luminaires is minimizing the need for repositioning the luminaire by the surgical team and minimizing the forces required for these actions. In that way, surgeons will be able to concentrate on their main task, and perform surgery in a well-illuminated wound and by a user-friendly lighting system.

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Part B

Paper ***'A Simulation Model of a Surgical Lighting System'***

A Simulation Model of a Surgical Lighting System

Keywords

Ergonomics, equipment, operating room technology, surgical lighting, usability

Abstract

Ergonomic problems of surgical lighting systems have been indicated by surgeons. A previously performed observation study pinpointed usability shortcomings of present surgical lighting systems, and concluded. However, a clarification of the underlying cause was not given. The aim of this study was the construction of a valid simulation model of the surgical lighting system to allow virtual experiments of the system mechanics to clarify the underlying causes. The model was constructed to simulate the Berchtold Chromophare C series. A valid simulation model of the surgical lighting system was constructed in MSC software Adams. The model showed that the required force during luminaire usage depends on the location of the luminaire its work field and are on average higher than ergonomically acceptable. Primary cause of this difficulty with the current systems is the two pendant arms construction as the highest forces were found when the luminaire was directly below the ceiling suspension or in the peripheral region of the work field. In those regions the pendant arms are either in parallel or serial alignment. The force spectrum for luminaire use showed a diffuse image, ranging from 14 Newton till unlimited quantities when the system is unmovable. The average required force is 136 Newton in the region where the observed luminaire use was primarily undertaken. In addition, the software engineering model which was constructed in this study is applicable as a test procedure to analyse surgical lighting systems. In addition, the software engineering model which was constructed in this study is applicable as a test procedure to analyse surgical lighting systems.

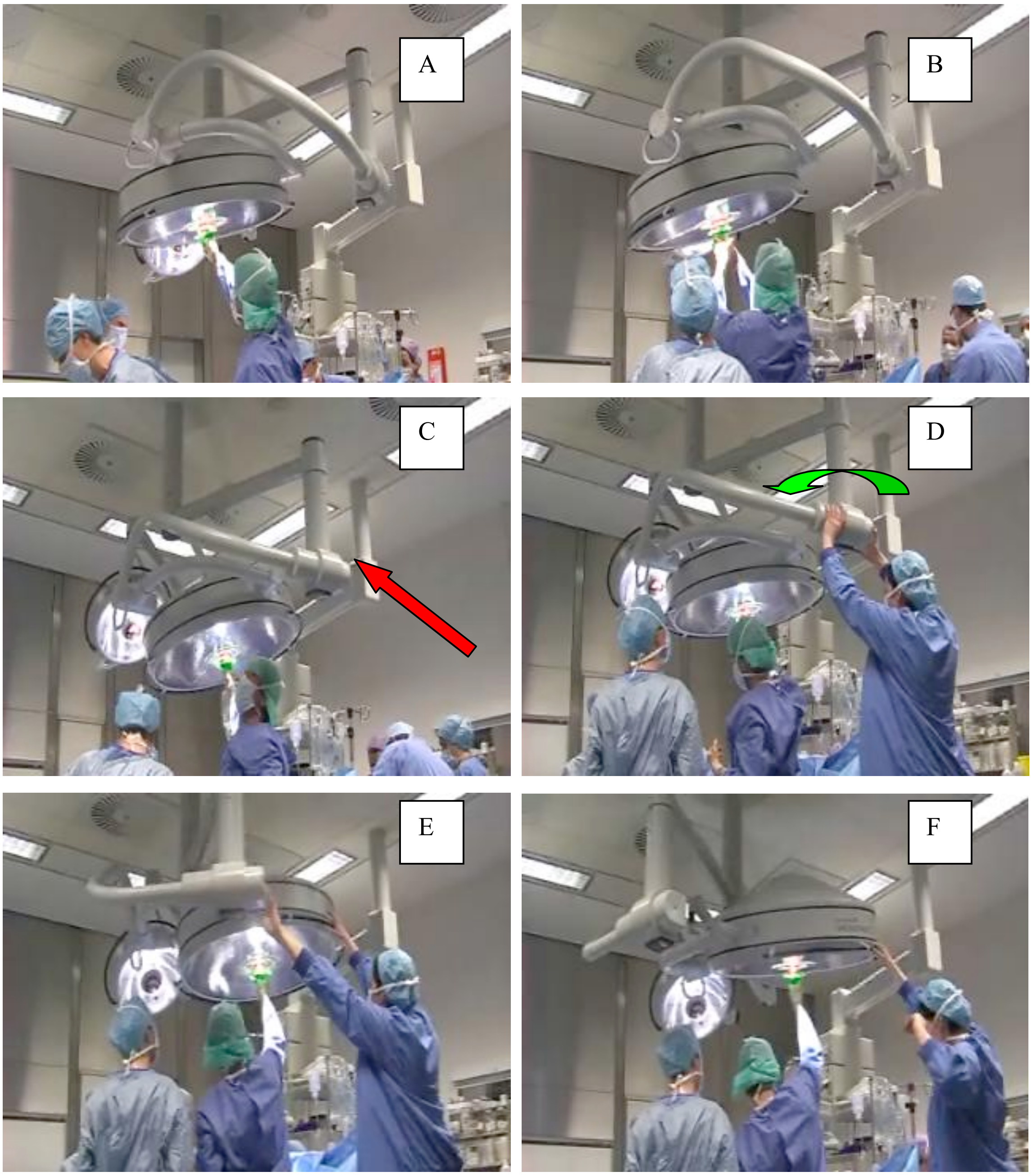
Introduction

For many years, illumination of wounds during surgery has been done by surgical lighting system (SLS), which basically consists of a large, heavy luminaire suspended from the wall or ceiling by a two-arm pendant system. The luminaire has been designed to supply high-intensity light to the wound. The diameter and intensity of the light beam can be adjusted and the pendant system has been designed to allow great flexibility in positioning of the luminaire and to stabilize the position of the luminaire in a certain position. Ergonomic shortcomings of the surgical lighting have been indicated by different authors via surveys among surgeons [2-5, 7-9, 11-13], and the need for ergonomic improvements of the lighting system has been stated [8, 9, 11]. Complaints varied from colliding pendant arms to heads banging against lights and from insufficient illumination to one-handed adjustments of the lights being impossible. But the scope of the problem was not studied in these papers, or the underlying causes.

A previous study [10] pinpointed the illumination and usability shortcomings of present surgical lighting systems as 46 hours of open routine surgical procedures in the field of general surgery was observed. Noted difficulties were collisions of the luminaire against any object; the luminaire was out of reach for the surgeon in a sitting posture; the principal difficulties were observed in the kinematic aspects of the SLS and user interaction, as luminaire manoeuvrability was cumbersome: luminaire relocations did not take place along the shortest route in 3D space (Fig. 10); and in some situations the SLS was immovable. These problems occurred during the repositioning of the luminaire in the two dimensional (2D) plane of the pendant arms of the SLS. Although this study presented unique insights in characteristic of the operating room (OR) lighting problem, it did not provide a clarification of stated problems.

The aim of this study was to construct a valid simulation model of the SLS, and attain insight in the required force for a luminairy action (LA) at various locations of luminaire in the SLS work field by model simulation. It was hypothesized that the required force for a LA is dependent of the luminaire location, and above the ergonomically acceptable limits. The SLS model was constructed in MSC Adams software to allow virtual experiments with the system mechanics via multibody dynamics analysis. The outcome of the simulation runs was visualized by a 2D map displaying the required forces for a LA for the luminaire locations in the work field.

Figure 10 - Pictorial presentation of a 'mechanical singularity' of the SLS during a LA.



1. **The medical staff member, as the performer, initiates a one handed luminairy action (LA) to reposition the luminaire [A];**
2. **The LP is unable to reposition the lamp by one hand and uses two hands to produce extra force on the luminaire [B];**
3. **The LP is still unable the reposition the luminaire in the preferred direction, which coincides with the parallel pendant system arms (indicated with the red arrow), resulting in a loss of degree of freedom. [C];**
4. **A second medical staff members is required to assist the LP with the LA, by rotating the pendant arms (indicated with the green arrow) [D];**
5. **The second medical staff member rotates the parallel system arm in a direction that is unequal to the direction preferred by the performer [E]; and**
6. **The prior LP is able the reposition the luminaire in the preferred position to complete the LA [F].**

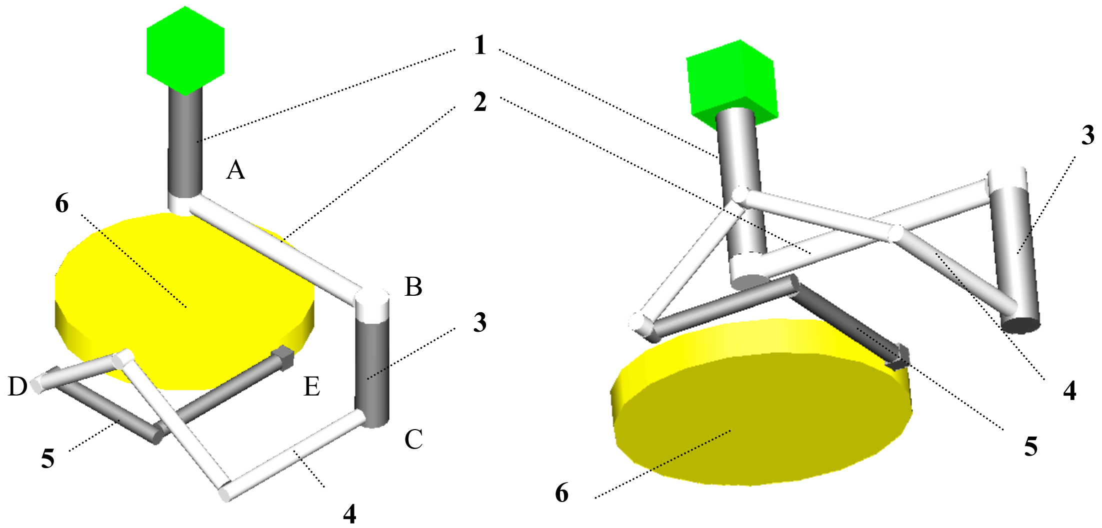
Material and Methods

Model construction
The SLS was modelled using MSC Adams version 2005 r2 as the software tool and 4 model assumptions:

(1) SLS is a rigid multibody system;
(2) SLS rigid body parts are slender rods segments;
(3) No margin error is present in the 1 degree-of-freedom (DOF) joints;
(4) Joint friction behaviour abides the Coulomb's law of friction.

The SLS mechanics is then defined by the mechanics of the individual parts and resistance behaviour of the system at the interconnecting joints. The SLS geometry and structure was simplified: Each part was shaped as a straight MSC Adams rigid body segment; the joints as revolute joints that also function as constraints between each body parts to restrain the SLS DOF and complete the outline of the model (Fig. 11). The individual joints and body parts were labelled with a number and simple quotation (Table 1).

Figure 11 - The SLS model outline from two viewpoints



The MSC Adams model of the SLS with the six rigid body parts: (1) flange tube; (2) horizontal swivel arm; (3) vertical tube; (4) hydraulic arm; (5) horizontal arm, and; (6) luminaire. The element in green acts a ground part and functions in MSC Adams as a base part on which the model was connected. (A) Horizontal swivel arm joint (B) vertical tube joint (C) hydraulic arm joint (D) horizontal arm joint (E) luminaire joint.

Table 1 - Quotation, number and segment topology at each interconnecting SLS joint.

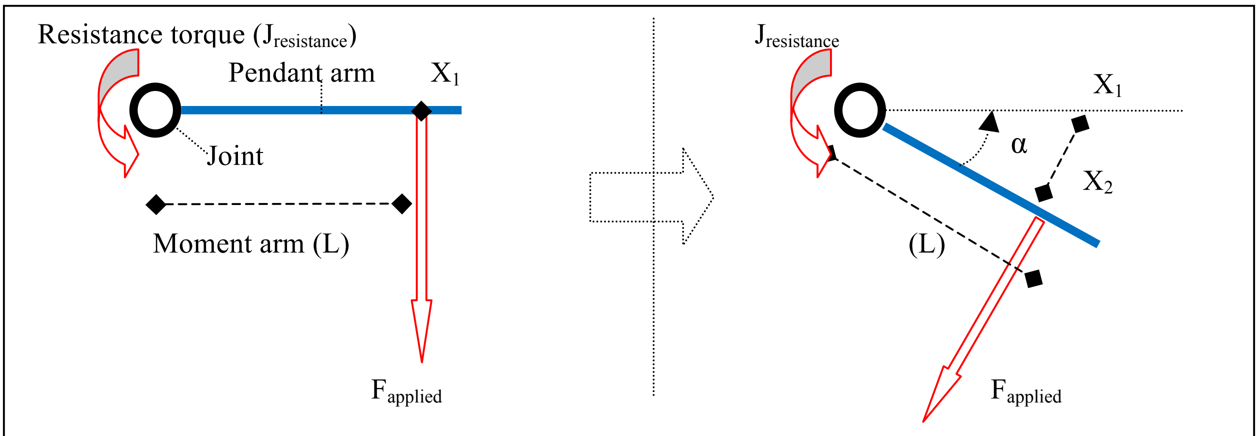
Joint nr.	*Label*	*Joint interconnect the rigid body segments*
1	Horizontal swivel arm joint	Flange tube & horizontal swivel arm
2	Vertical tube joint	Horizontal swivel arm & vertical tube
3	Hydraulic arm joint	Vertical tube & hydraulic arm
4	Horizontal arm joint	Hydraulic arm & horizontal arm
5	Luminaire joint	Horizontal arm & luminaire

The SLS model was based on a Berchtold C series SLS, the same system of the observation study that pinpointed the shortcomings of present SLSs [10]. Manual measurements were performed on this physical SLS, at the Reinier de Graaf Gasthuis hospital in Delft, to obtain technical data as input for the model construction and validation. The openly available Berchtold technical data contained global information: Total SLS mass is 121 kg.; maximal swivel radius luminaire is 190[1] cm; all joint friction mechanisms are passive; resistance of hydraulic joint is caused by a hydraulic technique and for the other joints by a friction plate mechanism.

SLS geometry was obtained using a tape measure. The sparse technical information made it necessary to define an extra assumption concerning the mass distribution; each part body was given a fraction of the total mass in the same ratio as the body part volume in relation to the total SLS volume; the luminaire then obtains the largest mass in the SLS. Since it was impossible to check the actual mass distribution, this approximation was taken into account during a model sensitivity analysis. The resistance behaviour was measured at each interconnecting joint with a force sensor (type ZFA loadcell 100kg) connected to an amplifier (type HBM DA 3418). The signal from the force sensor was stored via an AC data converter (NI-USB-6008: 12-Bit, 10 kS/s) on a PC, with Microsoft Windows XP operating software using NI (National Instruments) Labview version 8.2. NI Labview produced text files which were loaded into Microsoft Office 2007 Excel and Matlab version 2007 for data analysis and visual presentation. This resistance behaviour was done by manual measurement, carried out according to a protocol aimed to produce a constant low velocity of the body part in the dynamic region to annul the mass moment of inertia. To reduce possible errors during the measurement process, pilots were executed in advance.

Eighteen force measurements were performed on each individual joint (Fig. 12). On one side the force sensor was attached on a SLS body part using a tie rape; the other side was manually controlled; a force ($F_{applied}$) was applied manually at moment arm (L) perpendicular on the SLS body part to create a torque ($F_{applied}$*L) around the individual joint degrees in the plane of the 1DOF joint (Fig. 3). The SLS resistance behaviour to oppose joint motion at each was expressed as a torque ($J_{resistance}$). During each individual measurement, the joint was rotated an equal angle in a time span of 4.5 seconds along a tracked distance (X_1-X_2); Joint motion was visually observed while tracking the applied force trajectory. Time and force were noted at the threshold of motion to obtain the time duration and force magnitude of both the static and dynamic region. The dataset $F_{measurement}$ (N = 18 per joint) was divided into two equal sized sub-datasets and multiplied by its moment arm (L) to obtain the resistance behaviour as torques; T_{model_input} and $T_{validation}$. The average value per joint of T_{model_input} was used for the model approximation of the resistance behaviour; the average of $T_{validation}$ functioned as an independent dataset for the model validation.

Figure 12 - 2D top view of initial (left side) & end configuration (right side) of joint resistance measurement



The resistance torque ($J_{resistance}$) measurement is performed by manual applying a force, creating an applied moment ($F_{applied}$*L) on the joint to induce motion. This measurement was performed at each individual joint.

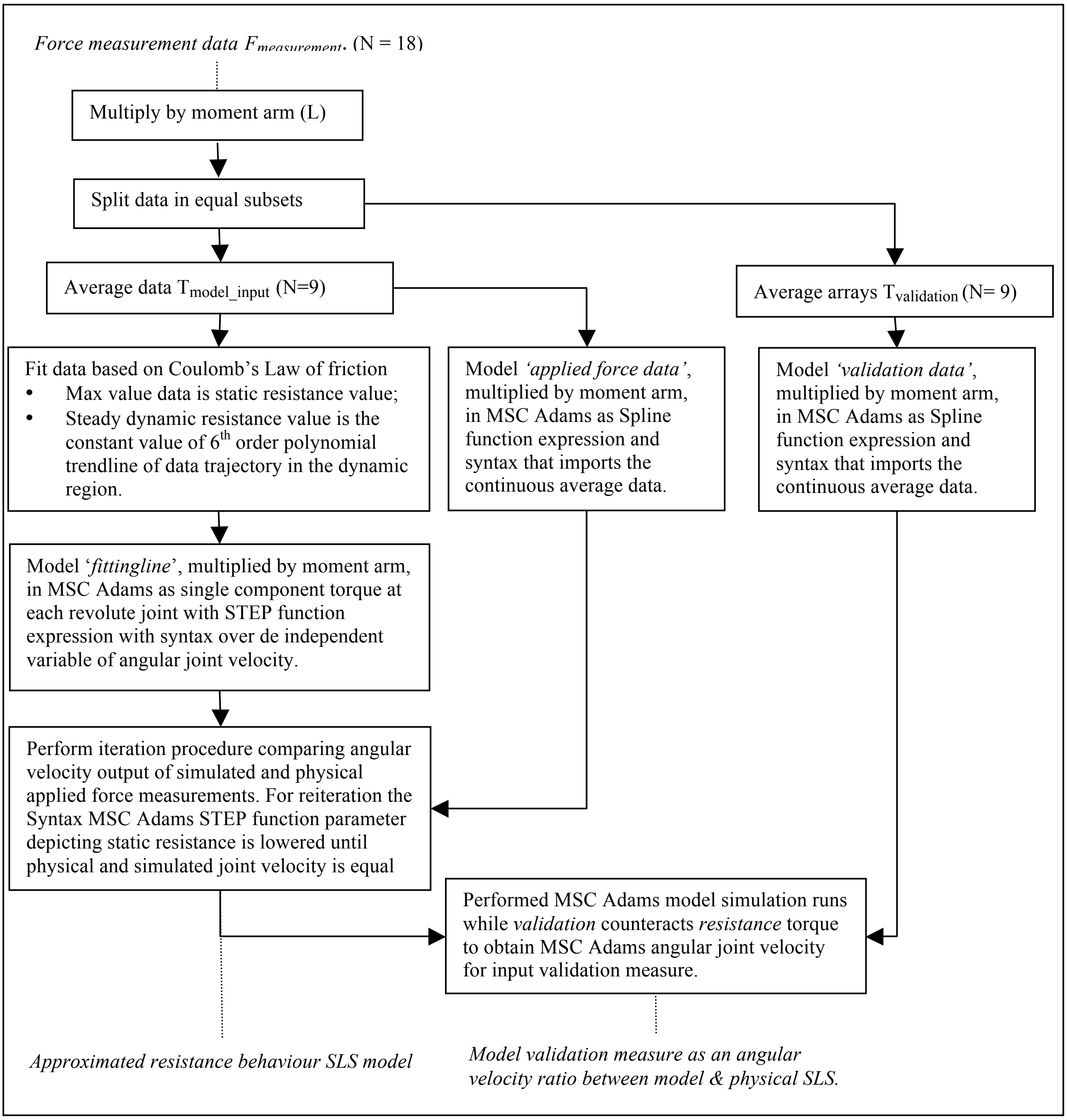
[1] Data based on self made measurements . Berchtold technical indicates a max. swivel radius of 193 cm [1].

The model resistance data was approximated at each interconnecting joint via an iteration method, which was assembled in three steps (Fig. 13):

(1) The average trajectory of T_{model_input} was fitted based on the Coulomb's Law of friction: The max value served as the static resistance; the constant value of 6th order polynomial trend line of trajectory in the dynamic region presented the dynamic resistance;
(2) Two counteracting single component torques were modelled in MSC Adams at each revolute joint with different syntaxes. One to simulate the applied torque, the other the resistance behaviour:
    a. The syntax for the modelled resistance torque was the MSC Adams STEP function expression, an apt algorithm to depict the behaviour of the Coulomb's law of friction. The algorithm provides in MSC Adams a means of transitioning from a constant value to another value of a function over a specified independent variable. For the initial iteration step the syntax was based on the fitted parameter of T_{model_input} in which the transition from static to dynamic parameter was dependent on the angular joint velocity of the SLS model;
    b. The syntax for the simulated applied torque was the MSC Adams SPLINE function expression, an apt algorithm to imported the mean of T_{model_input} so that the simulated applied torque has an identical behaviour as the physical applied torque;
(3) Simulation runs were performed for 4.5 seconds while the model was subjected to the simulated applied torque on one joint corresponding with the manually applied force, multiplied by its moment arm (L). After each run the angular joint velocity of the physical and model SLS were compared. The resistance data was adjusted for the reiteration until physical and simulated joint velocity is equal and the appropriate approximation of the resistance value is attained.

Model simulations were performed without force of gravity to reduce the possible effects of the unknown mass distribution. Due to the measurement protocol, the SLS model is only valid at low constant (angular joint) velocities, where viscous behaviour and mass inertia effects do no play a role in the system dynamics. Lastly, in order to increase the accuracy of the numerical integration of MSC the integrator command in MSC Adams was altered from GSTIFF to S12_GSTIFF integrator modus; so that the software can handle small integration time steps more effectively.

Figure 13 - Diagram describing SLS model construction of approximated resistance behaviour & validation.



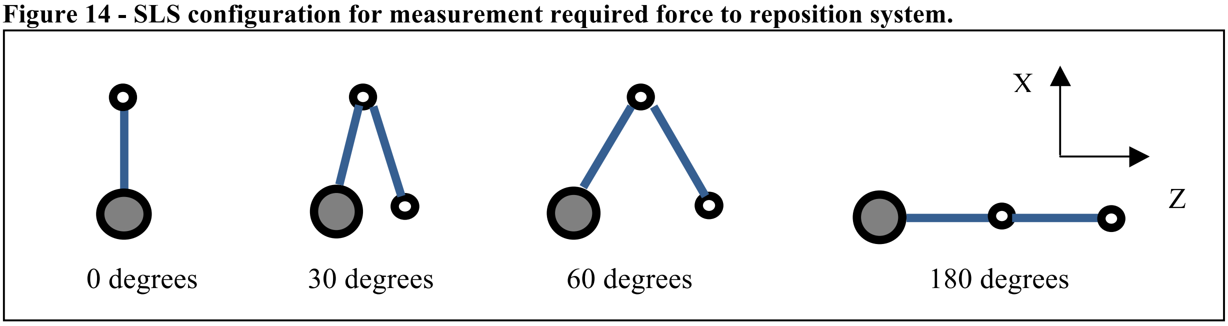
The reliability of the simulation model was verified by assembling the model according to the MSC Adams tutorial and subjecting the model to 4 debugging checks incorporated in MSC Adams. Model consistency was verified by repeating the validation simulations ten times and comparing the outcome.

The model validation was assessed in two alternative procedures:

- Procedure 1 provided a model validation measure as an angular velocity ratio between the model and physical SLS at each individual interconnecting joint. The SLS model with the approximated resistance behaviour was subjected during a simulation run by a MSC Adams single component torque with a SPLINE function expression with a syntax that imported the mean value of $T_{model\_validation}$. The resulting angular model joint velocity was compared with the tracked angular joint velocity during the physical force measurement to obtain the validation ratio;
- Procedure 2 provided a model validation measure as a force ratio for the SLS as a total by comparing the required forces to initiate a translational luminaire repositioning between the model and physical system at four system configurations (Fig. 14) in two force vector directions (X & Z).

A sensitivity analysis was performed to increase the confidence in the model by identifying the model sensitivity for the approximated parameters of the rigid body parts mass distribution and the resistance behaviour at the interconnecting joints; the SLS model output was calculated while the approximated variables were adjusted with a variance of plus & minus 10% of its normal values.

Figure 14 - SLS configuration for measurement required force to reposition system.



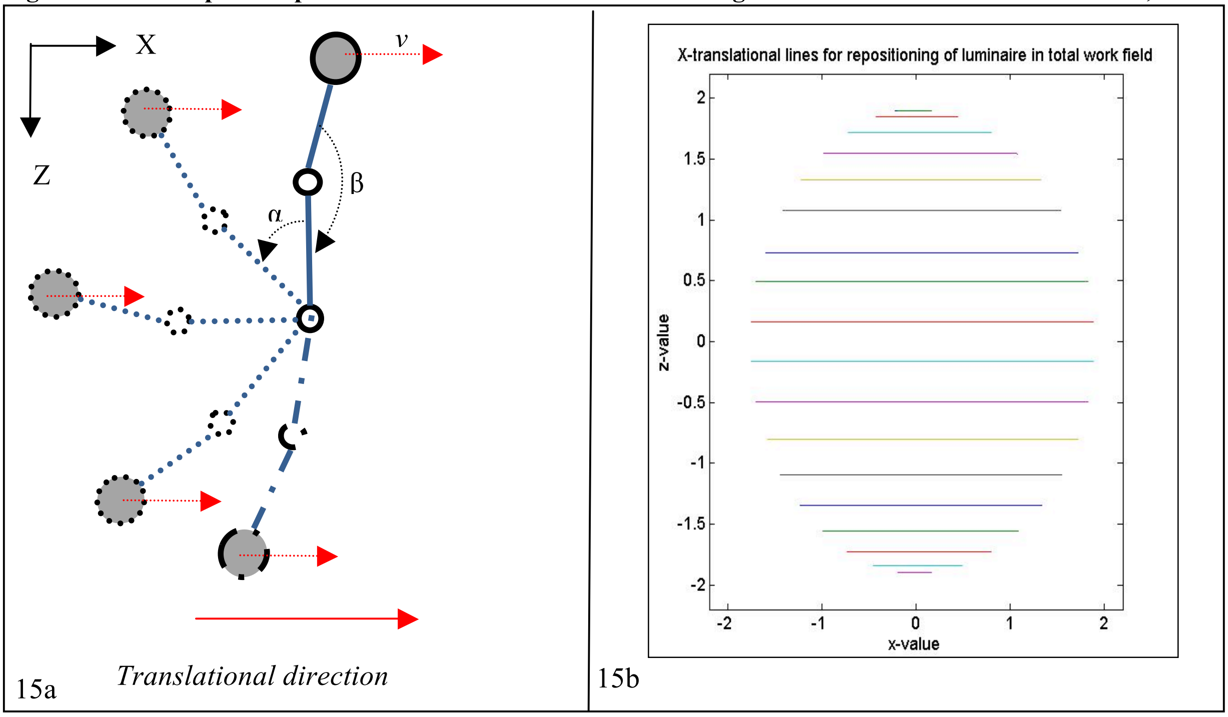
Top view of the 2D surgical lighting system (SLS) pendant arm configuration at four luminaire positions to measure the required force to reach the threshold of motion of the SLS as a total.

Model simulation runs

The constructed SLS model was used to perform simulation runs in which the luminaire was repositioned along a translational line under influence of an external applied force in the horizontal 2D plane of the pendant arms (Fig. 15). Simulations were run as x-translational repositioning of the luminaire along a constant z-axis in the work field with a velocity of 0.1 m/seconds and a MSC Adams step size of 0.1 seconds. The information of the luminaire position and required translational forces was used to generate a contour plot of the required forces for luminaire repositioning in the SLS work field.

A simulation was run until system lock up was detected, in which case MSC Adams would terminate the run as the model constraint(s) can no longer be satisfied, when the luminaire was at boundary of the modelled SLS work field. The initial SLS model configuration was depicted to overcome a system lock up (the so-called gimbal lock) at the initiation of the simulation run (Fig. 15a); beta (β) was 170 degrees. Different x-translational lines were achieved by rotating the initial model configuration along and angle alpha (α) of ten degrees after each simulation run to obtain a total of N = 18 simulation lines (Fig. 15b). Translation lines during which an exact parallel alignment of the pendant arms would be reached were omitted in the generated force map. Inclusion of that data would produce a discontinuous image in the contour map, as the position vector of the luminaire has limited elements.

Figure 15 - Conceptual representation of SLS initial model configurations for X-axis simulation runs, N = 18.



<u>15a:</u> Above are shown 5 initial configurations of the SLS model. 18 simulation runs were performed with varying Z-values. During the simulation run the model luminaire was repositioned along the X-axis in its work field. The initial system configurations for the first simulation run are outlined in solid lines, the last simulation run configuration is outlined in dash dot lines and three in between initial system configurations are outlined in dashed lines.
<u>15b:</u> The 18 translational lines of the luminaire in the SLS work field.

The simulation data output were exported from to MSC Adams to a Microsoft Excel tab file. In Microsoft Excel the first and last column elements were deleted to eliminate the start and end behaviour of the simulation run. These elements are improper as they are the result of the MSC Adams numerical calculation of a discontinuous situation: The abrupt transition between zero and the constant velocity of the luminaire. The Microsoft Excel data sheet was in turn imported into Matlab version 7 to allow data processing and visualization of the acquired two dimensional force - luminaire location mapping. The required forces in the x- and z-directions during the luminaire translational simulations were computed into one resultant force, $Ft = [(Fx)^2+(Fz)^2]^{1/2}$. The forces in the data sample were maximised in Matlab at 600 Newton to limit the simulated forces of the model lock. In MSC Adams these force can reach extreme values before simulation is terminated.

A force spectrum of the required force (Ft) for translational repositioning of the luminaire in the simulation model was calculated by presenting mean, maximum, minimum and standard deviation in three regions of the SLS work field:

- *Region1 = Central work field*: In this region the system pendant arms are (almost) in parallel configuration and the moment arm (L) is at max 47.5 cm., equal to the radius of the luminaire;
- *Region2 = Mid work field*: The luminaire is in the region between the central and peripheral field, and the angle between the pendant arm is in a range of: $47.5 \leq L \leq 187$ cm;
- *Region3 = Peripheral work field*: The luminaire is in the peripheral region. The pendant arms are (almost) in serial configuration, and L is in a range of: $190 \leq L \leq 190$ cm.

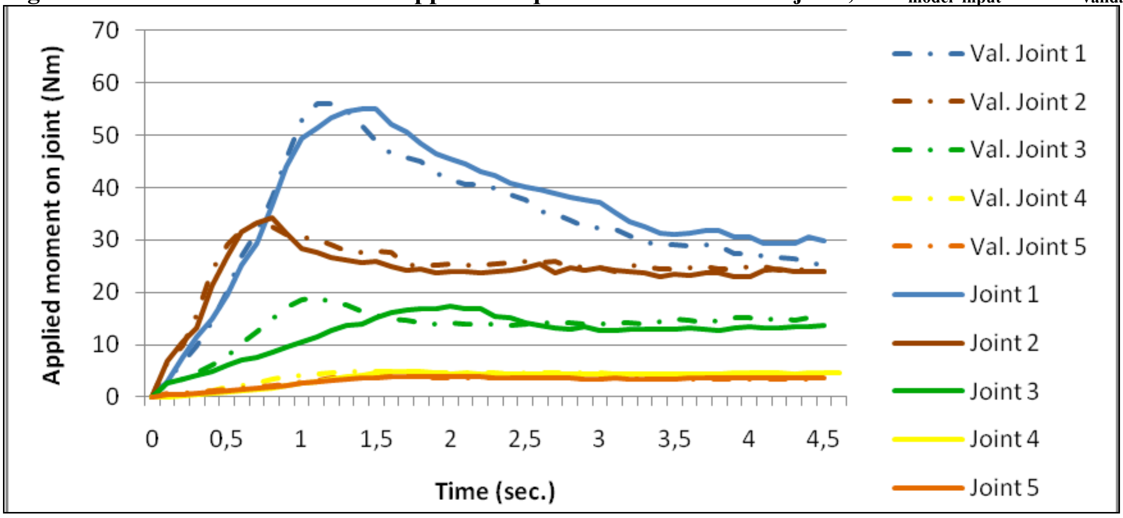
Results

The depicted method resulted in the construction of a reliable and consisted model of the Berchtold C series SLS. The MSC Adams debugging checks did not depict errors and no variance was detected during the repetition of the two model validation procedures.

Both a visual inspection (Fig. 16) and regression analysis of the two datasets illustrated that the measurement was performed consistently and that the assumption of Coulomb's Law of friction is proper. The goodness of fit (R^2-value) all the five joints between two datasets T_{model_input} and $T_{validation}$ was proximate 1 with a significance of fit (overall p-value) below 0.05. This also implied that the two subsets were beneficial for the model validation, as each set should result in equal model simulation output. It should be noted that the resistance behaviour of joint 1 had a relatively long time duration from the threshold of motion to the constant dynamic (2.4 seconds), combined with the angular velocity presumably indicates an undesirable high acceleration at the start of the joint motion (Table 2).

As to be expected, the fitted parameters of T_{model_input} (table 2) depict that joint 1 has the highest static and dynamic resistance values as the central joint of the SLS. Subsequently joint 5 has the lowest resistance values as the most peripheral joint in the system connected to the luminaire.

Figure 16 - The mean of measured applied torques at each individual joint, of T_{model_input} and $T_{validation}$.



The mean of the applied torque measurements to initiate joint motion in the sub-dataset of model input (T_{model_input} = 9,) sub-dataset of model validation ($T_{model\_validation}$ = 9). T_{model_input} is presented in solid lines, while $T_{model\_validation}$ is presented in dash dot line style. Joint 1 is in the blue colour, joint 2 has a brown coloured line, joint 3a green colour, joint 4 a yellow colour and joint 5 has an orange colour.

Table 2 - The fitted resistance friction torque parameters of T_{model_input} for each individual joint, N = 9.

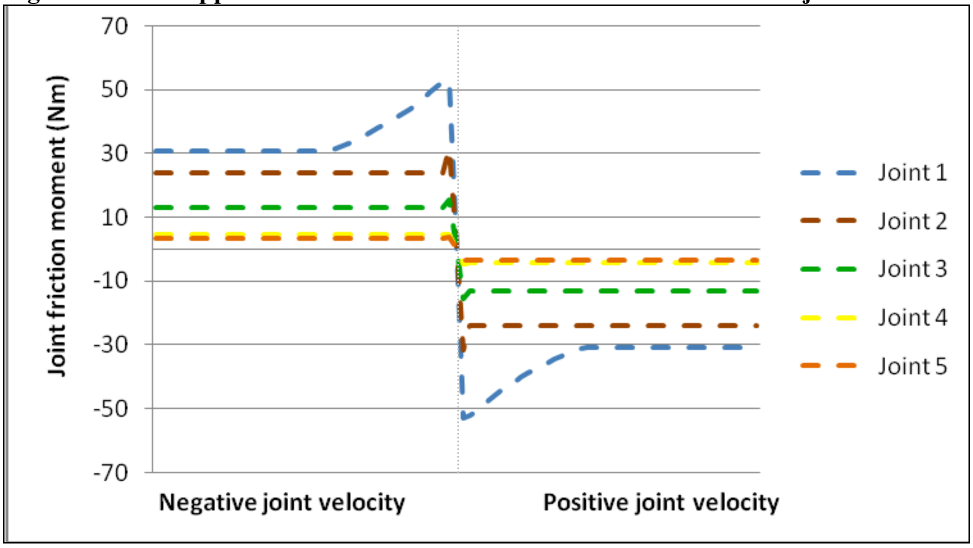
Joint nr.	*Torque at threshold of motion (Nm)*	*Measurement time at threshold of motion (sec)*	*Average dynamic friction (Nm)*	*Measurement time at start average dynamic friction(sec)*	*Angular velocity joint (Degrees/sec)*
1	55.1	1.4	30.8	3.5	12
2	34.2	0.8	23.9	1.6	6
3	17.3	2	13.1	2.7	6
4	4.9	1.6	4.4	2.5	8
5	3.9	1.6	3.5	2.6	12

During the iterative method the approximated resistance behaviour at each interconnected model joint was obtained by lowering the parameter depicting the static resistance in the STEP function syntax of the fitted parameters of T_{model_input}, with a kinetic friction that is independent on the sliding velocity according the Coulomb's Law of friction (Fig. 17).

A relevant aspect occurred in joint 1. To obtain an equal angular joint between the real life and simulated applied force measurement, the assumption of Coulomb's Law of friction was not fully applicable for the approximated friction behaviour. The dynamic resistance behaviour was up to a speed of 11.55 degrees per seconds dependent on the angular joint velocity (Table 3). It is credible to assume that inertia effects were incorporated during the joint resistance behaviour measurement. It is impossible that the joint shows a viscoelastic or viscous friction behaviour since joint 1 is a passive plate joint.

But the performed sensitivity analysis showed that possible errors and assumptions in the approximated parameters does not affect the significance of the the insights gained from the SLS model. The resulting output variance was trivial under a 10% variance of the approximated input parameters. In contrary with the above, an adjustment in the SLS pendant arm geometry that alters the pendant arm length does have an impact on the SLS model force output.

Figure 17 - The approximated resistance behaviour at each individual joint in MSC Adams, N = 9.



The trajectory of the approximated coulomb friction behaviour simulated in MSC Adams. joint 1 = dashed line blue colour, joint 2 = dashed line brown colour, joint 3 = dashed line green colour, joint 4 = dashed line yellow colour and joint 5 = dashed line orange colour.

Table 3 - Approximated resistance behaviour at each joint in MSC Adams, N = 9.

Joint nr.	*Static torque (Nm)*	*Average dynamic torque (Nm)*	*Angular joint velocity at start dynamic region (degrees/ sec)*
1	53.25	30.8	11.55
2	33.4	23.9	0.03
3	18.4	13.1	0.03
4	4.75	4.4	0.03
5	3.8	3.5	0.03

The two model validation procedures indicated that the SLS model is a valid representation of the physical SLS, as both the angular velocity ratio (Table 4) and the force ratio (Table 5) illustrate that the differences between physical and model SLS are in the same order of magnitude.

Table 4 - Model validation measure as a velocity ratio at each individual joint of the model and physical SLS.

Joint nr.	*Angular joint velocity with the input simulation data (Degrees/sec)*	*Angular joint velocity with the validation data (Degrees/sec)*	*Ratio between input and validation data*
1	12	13,1	1,1
2	6	8,7	1,4
3	6	7,8	1,3
4	5	7,7	1,5
5	12	14,2	1,2

The validation measure of the SLS model is calculated at each individual joint, between the tracked angular joint velocities in the sub-dataset $T_{validation}$ and simulated angular joint velocities in the model based on the sub-datasets T_{model_input}.

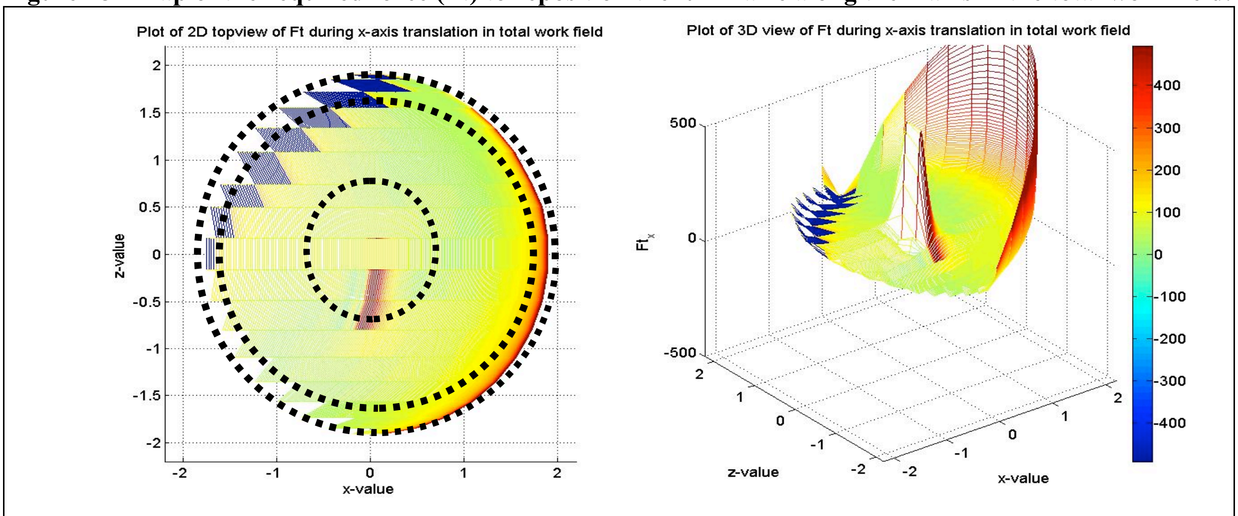
Table 5 - Model validation measure as a ratio between required force to initiate luminaire repositioning in the model and physical SLS.

Force direction	*Validation ratio at the each surgical lighting system configuration*			
	0 degrees (parallel)	*30 degrees*	*60 degrees*	*180 degrees (serial)*
X-positive	1	1.2	1.4	1.1
X-negative	1	1.2	1.3	1.1
Z-positive	1.1	1.3	1	1
Z-negative	1.1	1.3	1.3	1

The generated contour plot of the required forces for luminaire repositioning in the SLS work field displayed non-uniform force fields (Fig. 18). Then again, the force spectrum displays a very high variety for the three regions in the SLS work field (Fig. 19):

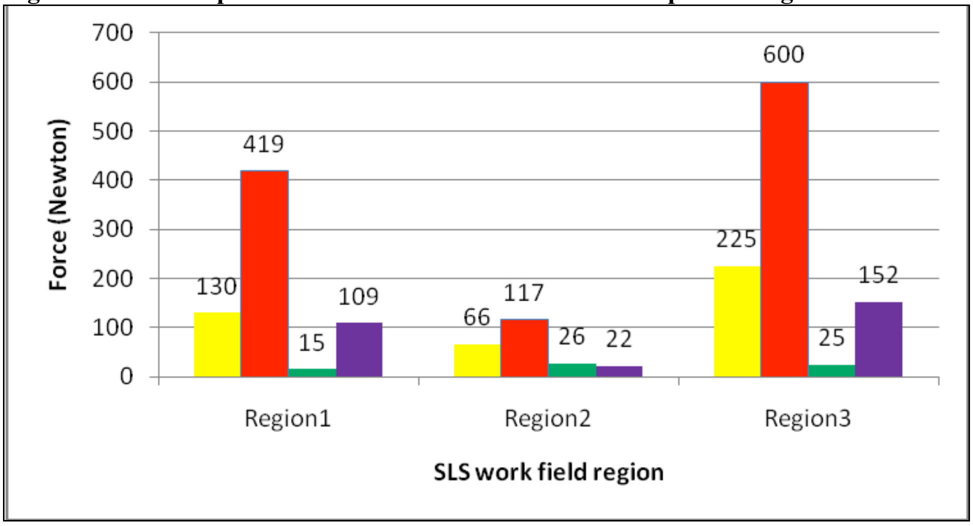
- The maximum forces occur in the central and outer regions, which also display the highest diversity in the force spectrum;
- The mid field region with an average force of 65 Newton and a maximum force of 117.5 Newton displays the lowest variety and average in required forces;
- The minimum forces for all three regions are low and in the range of 14 - 26 Newton;

Figure 18 - Map of the required force (Ft) to reposition the luminaire along the x-axis in the total work field.



Map of the required force (Ft) to reposition the luminaire along the x-axis in the total work field. The vertical colour bar on the right indicates the force value scale of the map in the range of 500 until -500 Newton. In the left 2D map the three SLS work field were incorporated. The boundary of the work field regions are formatted as the dashed black colour line.

Figure 19 - Force spectrum of X translational luminaire repositioning in work field



Mean (yellow column), maximum (red column), minimum (green column) and the standard deviation (purple column) of the required force (Ft) during the X translational repositioning of the luminaire in each SLS work field region.

Discussion

This study presented the construction of a valid SLS model of brand Berchtold and type C series in MSC Adams software, an explanation for the observed usability shortcomings of the surgical lighting systems of this SLS brand Berchtold and type C series and it presents a protocol to analyse the SLS using engineering software simulation.

The simulation model confirmed that the force to reposition the luminaire is dependent on the location of the luminaire in the work field. It also confirmed that the cause for this kinetic behaviour is due to the mechanism of the SLS of the system pendant arms. The highest force peaks were noticed at the centre of the work field, where the system pendant arms are in (near) parallel alignment. And in the peripheral region of the total work field, where the system pendant arms are again in a (near) gimbal lock due to (near) serial alignment.

Also, on average the required forces are higher than ergonomically acceptable. The ergonomically acceptable forces a human should exert on external bodies with his upper extremities (hand and arm) depends on the force direction and the location of the interaction between human and the body in relation to one own position: A LA performed at head heights and close proximity of the LP should be in the range of 28 till 62 Newton for forwards and backwards motions, or 11 or 13 Newton for inwards or outwards motion [6].

The combination of these findings could be the explanation why the observed luminaire relocations did not take place along the shortest route in 3D space [10]. The user of the SLS will encounter a lower and ergonomically acceptable during the repositioning of the luminaire through the mid field region, that a reposition of the luminaire strictly in the central or peripheral work field.

Another question that arises is whether the selected data sample is representative for the larger field of surgical procedures. The external validity of the conclusions is prohibited to an SLS of the brand Berchtold and type C series. Due to these limitations some problems that are specific for certain SLS brand might be overlooked. However, the general problem of a non-ergonomically kinematic relation between the user and the SLS are likely to be valid for a larger dataset of other SLS brands and types, since the user system interaction in general entails the same three interaction variables. The validity of this statement is higher if the SLS luminaire manoeuvrability is acquired with a two arm pendant configuration, as the required forces are predominantly dependent of the SLS pendant arm geometry.

In addition, the software engineering model protocol that was depicted in this study is deemed applicable as a test procedure to analyse a SLS of other brands and type in MSC Adams software, as the presented model construction method supplied a valid and reliable simulation model.

Conclusion

In conclusion, this study illustrated the construction of a valid and reliable simulation model in MSC Adams of a Berchtold SLS. The SLS model allows virtual experiments with the luminaire to obtain insight into the system mechanics to clarify the obtained insights from the observation study [10]. Due to the measurement protocol and assumptions, the model is valid for low angular joint velocities.

The simulation model confirmed that the force to reposition the luminaire is dependent on the location of the luminaire in the work field, and caused by the configuration of the two pendant arms of the surgical lighting system. Also, the required forces were on average higher then ergonomically desirable, but the force spectrum displays a very high variety for the three regions of the SLS work field

A possible improvement of the SLS should be focused on the improvement of the kinetic relation between the system and user. In that way, surgeons will be able to concentrate on their main task, and perform surgery in a well-illuminated wound and by a more user-friendly lighting system.

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Part C

Appendix *'Research report'*

Abstract

Ergonomic problems of surgical lighting systems have been indicated by surgeons; however, the underlying causes are not clear. The aim of this dissertation is to assess the problems in detail, and subsequently clarify the underlying causes.

In the first stage of the research, the observation method was used to quantify the luminaire use during 46 hours of open routine surgical procedures in the field of general surgery. The location of the observation study was the Reinier de Graaf Gasthuis hospital in Delft, which employs the Berchtold C series as the surgical lighting system. The results showed that every 7.5 minute a luminaire action takes place, intended to reposition the luminaire. Of these LAs, 74% was performed by surgeons and residents. For 64% of these LAs the surgical tasks of OR-staff were interrupted. Observed difficulties were collision of the luminaire against any object, or that the luminaire was out of reach for the surgeon in a sitting posture. The primary difficulty appeared in the kinetic relation during the SLS and user interaction, as luminairy repositioning required visible high forces, the manoeuvrability was cumbersome and in some situations the system was immovable. These problems primarily occur during the repositioning of the luminaire 2 dimensional plane of the pendant arms.

In the second research stage a valid simulation model of the surgical lighting system was constructed in MSC Adams software to allow virtual experiments of the system mechanics. The model showed that the required force during luminaire use depends on the location of the luminaire its work field and are on average higher than ergonomically acceptable. Primary cause of this difficulty with the current systems is the two pendant arms construction as the highest forces were found when the luminaire was directly below the ceiling suspension or in the peripheral region of the work field. In those regions the pendant arms are either in parallel or serial alignment. The force spectrum for luminaire use showed a diffuse image, ranging from 14 Newton till unlimited quantities when the system is unmovable. The average required force is 136 Newton in the region where the observed luminaire use was primarily undertaken. In addition, the software engineering model which was constructed in this study is applicable as a test procedure to analyse surgical lighting systems.

As a result, this dissertation stated novel insights into the OR lighting problem during open routine surgical procedures in the field of general surgery. And it presented a valid simulation model of a surgical lighting system Berchtold Chromophare C series. The protocol for the model construction can be user to analyse surgical lighting system of different brands using engineering software simulation. Furthermore, this dissertation presented a direction for future research and an improved user system interaction of the luminaire during surgical procedures.

Table of contents

1. Introduction

1.1 Introduction

This chapter explains the research context of the dissertation and defines the rationale of the study. It presents the research questions that guide the study and introduces the methodology of the work. After this chapter the orientation, observation and its analysis will be presented in separate chapters, followed by the construction of the simulation model of the surgical lighting system, the result of the simulation runs with this model and the final conclusion, discussion and recommendations. To conclude, a brief summary of each chapter is presented.

1.2 Research Context and Rationale

The operation room *(further: OR)* is a complex environment. There are a multitude of people and devices present, which interact to perform a - possibly difficult and complex - surgical procedure. Also, the evolution of technology has led to a further increase of complexity. The introduction of new technologies lead to a growing number of - complex - devices and increased interaction between humans and technology.

The complexity of the OR environment can lead to potentially dangerous situations [16, 22]. Investigations - surveys among surgeons - about the working conditions and functionality in the OR report elementary deficiencies, and that these deficiencies lead to potential hazards for patients and personnel, potentially on a frequent basis [22]. The social quest is to identify and eliminate these potential hazards, so that in the future every patient would be operated on in the best-equipped, staffed, most modern operating room.

Non ideal OR lighting is a main source of hazards in the OR [21, 22], only second after the tripping hazards due to cables and tubes lying around in the room. The identified problems are various, for instance the operating field is not properly illuminated, and surgeons banging their head against the system and reposition of the OR lamp is difficult. Since it is broadly accepted that OR lighting is an important tool during the surgical procedures it has to meet high requirements. These requirements are now insufficiently met. Therefore, improvement of the OR lighting system is necessary.

Due to limited insights, the scope and the solution to the OR lighting problem is not at hand. The available research papers only state the problem, but do not describe the characteristics and scope of the problem or the solution. At the TU Delft Biomedical Engineering department the LIFE OR project has started (see Appendix A for more information about the project) to develop an improved OR, including the OR lighting system. At the moment, the project is in its investigating phase.

Exploration of the OR lighting problem requires insight into the use of the surgical lighting systems by the medical staff during surgical procedures. This is because OR lighting problem is the result of an insufficient interaction between user and system. The combination of the capabilities of the user - surgeon - and the possibilities of the system - surgical lighting system - defines the end result. Therefore, insight into the interaction between the user and system is obligatory to get an understanding of the perceived problems.

1.3 Research problem, goals and questions

The focus of this research was to explore and investigate, from a biomedical engineering point of view, the problem that the medical staff members perceive with the OR surgical lighting system during surgical procedures.

This study had three goals:

1. To gain insight into the use of the surgical lighting system by members of the medical staff during surgical procedures in the field of general surgery; and

2. To clarify the cause of the problem for the use of the surgical lighting system by members of the medical staff during surgical procedures in the field of general surgery; and

3. To indicate possible improvement of surgical lighting systems with the acquired insights of this dissertation.

This study was guided by the following methodological and empirical research questions:

1. What is the current state of information regarding the OR lighting problem?

2. How can one effectively illustrate the user and surgical lighting system interaction during surgical procedures?

3. On the basis of the obtained data (c.f. research question 2): What is the scope of the OR lighting problem during surgical procedures?

4. What are the two primary criteria that can improve the use of the surgical lighting system?

5. What can be used as a test procedure to analyse various surgical lighting systems with task assignments?

1.4 Research design

This research was an explorative study that utilizes two scientific research tools: the observation study, and the experiment in the form of a software simulation model.

To answer the research questions, the dissertation is structured as follows. In the second chapter the theoretical frame work is presented with the existing information and insights about OR lighting. In the third chapter the observation method is presented to collect data about the interaction between the surgeons and other medical staff members with the surgical lighting system during surgical procedures in the field of general surgery. This procedure of observing a medical operation is also referred to as a perioperative observation. In the fourth chapter the scope of the OR lighting problem is given by the results of the observation tool. Chapter five describes the construction of a software simulation model of the surgical lighting system, as the second scientific tool, aimed at exploring and analysing the primary problematic criteria witnessed in the observation. The sixth chapter presents the analysis of the simulation model data. In the seventh chapter the conclusions, discussion and recommendations for further research can be found.

2. Clinical setting of the research problem

2.1 Introduction

This chapter focuses on the first research question of the current state of information of the problem with the surgical lighting system (*further: SLS*). Paragraph 2.2 gives the setting of the operation room, followed by Paragraph 2.3 that presents some of the problems that the medical staff experience during surgical procedures. Paragraph 2.4 describes the problem with SLS that surgeons experience during the surgical procedure which is basically an interaction problem between the user and the luminairy system. The final Paragraph 2.5 states the conclusions of this chapter.

2.2 The setting of the operating room (OR)

The hospital establishes a well-suited environment to perform surgical procedures. Surgery is a medical specialty that uses operative manual and instrumental techniques on a patient to investigate and/or treat a pathological condition such as disease or injury, to help improve bodily function or appearance, or sometimes for some other reason. Over the year's surgery developed quite rapidly with the scientific era. In order to minimize and control infection patients were treated in specific places in which a sterile environment could be created more easily. Not only the locations, but also the surgical procedures changed over the years.

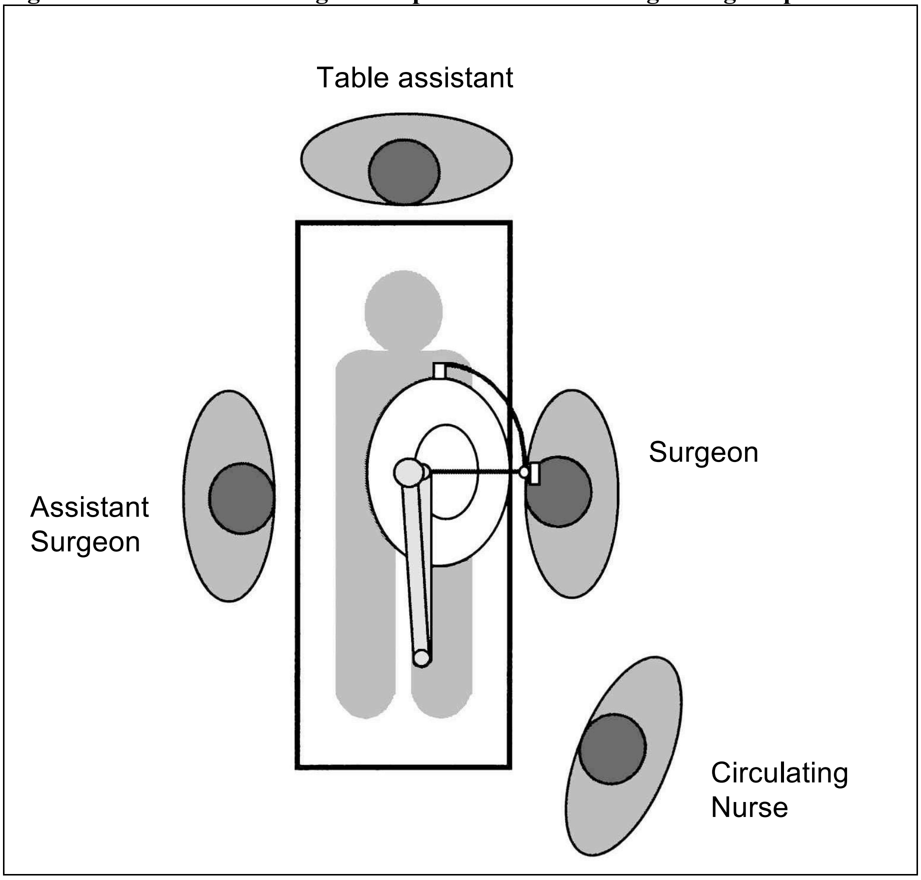
Nowadays, there are three types of surgery, categorised by degree of invasiveness of the surgical procedures: open surgery (also called invasive surgery), laparoscopic surgery (also called minimal invasive surgery) and non-invasive surgery [13]. A medical procedure is strictly defined as *non-invasive* when no break in the skin is created. An *invasive procedure* is one which penetrates or breaks the skin or enters a body cavity. In open surgery the surgeon views the patient tissue directly and in laparoscopic surgery the viewpoint is indirectly via a camera. There are other ways to categorize surgical procedures, for instance by urgency, type of procedure, body system involved the instrumentation used.

There is quite an amount of material present in the operation room to fulfil a surgical procedure. First of all, the patient is positioned on an OR table, which is surrounded by all kinds of OR apparatus from anaesthetic devices to PCs and monitors to check and monitor vital information. In order to get a clear visualization of the operation field the operation room contains an OR SLS. Lastly, surgeons perform medical actions with the use of instruments. All in all, the operating room is a complex workspace that requires multiple people to control the process and the outcome of the surgical procedure.

Two types of medical staff are present in the operation room to smoothly carry out the surgical procedure: (1) the anaesthetic, and (2) the surgical team. The anaesthesiologist is a medical doctor trained to administer anaesthesia (e.g. a drug) and manage the medical care of patients before, during, and after surgery. The surgical team is directly concerned with the surgical activity, and has four different staff members that (Fig. 20):

1. the surgeon(s) – multiple surgeons can be present in the room;
2. the assistant surgeon;
3. the table assistant (or first assistant); and
4. the circulating nurse;

Figure 20 - The static setting of an operation room during a surgical procedure.



The static operation room setting depicts the arrangement of the four medical staff members around the operation table, with patient, during surgical procedures [4], page 18.

Together with the aid of a surgeon, the surgical procedure was defined to undergo 3 phases to complete a medical operation:

1. *Initializing*: This initial stage starts when the luminaire is turned on and the operation is about to start - all medical staff members are in their required position as depicted in Figure 20, but no surgical activity (incision) has taken place yet.
2. *Surgery:* The physical intervention of surgery on the patient's tissue is defined in 3 subparts:
   I. Opening - from first incision to the placement of retractors;
   II. Operating - from placement of retractors until removal of the retractors. This is the stage in which the objective of the surgical procedure is carried out in the wound.
   III. Closing - from removal of the retractors until the last stitch;
3. *Finalizing:* The surgery is finished. In the final stage the wound is closed, but still some finishing actions to the patient are being performed. The surgical procedure is finished when the last bandage over the closed wound is applied by a medical staff member.

2.3 Problems medical staff experience

Surgeons experience problems with the use of devices during surgical procedures in the operating room. This was the conclusion of the studies performed by Mattern [22] and Patkin [21] but also from similar studies by Van Veelen [23] and Berguer [5]. The signalled problems are various, for instance tripping hazards due to cables and tubes, uncomfortable posture for hands and arms when using instruments, difficult positioning of the patient on the OR table and insufficient illumination of the operation field. Although the problems do not occur during every surgical procedure and some surgeons learn to deal with the imperfections, it seems that the deficiencies can have elementary consequences.

The previous mentioned studies all used the survey research method to investigate the working conditions and functionality in the OR among surgeons. Mattern [22] and Patkin [21] focused on the medical staff of laparoscopic and open surgical procedures. Mattern's study contained N = 425 surgeons, active in a number of different surgical disciplines – from general surgery to plastic surgery. Patkin's [21] study contained N = 40 surgeons from undisclosed medical disciplines. Van Veelen's [23] en Berguer's [5] did not mention statistics, but focused on the signalling of possible deficiencies. So it is vital to realize that the studies only focused on the experience of surgeons, and that reported problems are a perception of a situation.

According to the estimation of the interviewed medical staff the deficiencies in the OR during surgical procedures lead to potential hazards for patients and personnel, potentially on a frequent basis. A global number is not present, but 97 % of the participants in Mattern's study deem ergonomic improvement of the OR necessary. The occurrence of hazards takes place in various fields of surgical procedures. All studies plea that further research is necessary, since the results display a high potential for improvement in the OR.

The main problem is the complexity of the OR environment. There are a multitude of people and devices present, which interact to perform a – possibly difficult and complex– surgical procedure. Also, the development of technology has led to a further increase of complexity. The development of new technologies lead to a growing number of - complex - devices and increased interaction between humans and technology.

Each problem field is not experienced as equally grave. The interviewed medical staff had the opportunity to state what in their opinion needs ergonomically improvement in the OR. Next to the arrangement of cables and tubes, OR lighting was mentioned most often (by surgeons), followed by device handling, instruments and handles, OR tables and footswitches. This dissertation will focus on the disapproval among surgeons about OR lighting during surgical procedures.

2.4 The OR lighting is one of the main problems for surgeons in the OR

A SLS consists of a large, heavy luminaire and a small auxiliary luminaire suspended from the wall or ceiling by a two-arm pendant system. The SLS luminaire is positioned above the patient on the table in order to light the operational field during the surgery (Fig. 21). An SLS luminaire is designed such that high-intensity light is supplied to the wound while minimizing shadows of heads and hands of the medical staff member. The two arm pendant system has been designed to allow great flexibility in positioning of the luminaire and to stabilize the position of the luminaire in a certain position. The research problem is further explained below.

Figure 21 - An observed OR setting in the study.

The observed operation room setting has a surgical lighting system of the brand Berchtold, which illuminates the operation field during the invasive open surgical procedure with both the main and satellite luminaire.

The surgeons' disapproval with the OR light is a perception statement. Although a valid statement made by a (medical) expert in his/her field of expertise, it is not necessarily true that the surgical lighting system is the sole problem. Although his focus is on the OR light, the perception is actually a statement about the desired outcome of the interaction between the medical staff member and surgical lighting system. So basically the user-system interaction is insufficient of which the end result is influenced by a combination of the (in)capabilities of the user and the (im)possibilities of the system. Therefore, it is the interaction between the user and the system which is important.

The fundamental question is: 'Does the user or the system define the end situation?' The surgeon's disapproval implicitly means that the relation between him and the SLS is insufficient to reach the desired result. The surgeon is trained to work in the OR, so one can assume his judgment about the end result of the interaction is valid. On the other hand, the surgeon is not an expert in the user system interaction: therefore it is not reasonable to assume the surgeon is capable to point out the potential cause of the insufficient outcome.

The identified problems are various. For instance: the operating field is not properly illuminated by the OR light, surgeons banging their head against the system, or repositioning of the SLS luminaire is difficult. These unwelcome outcomes of the interaction can have two causes, or a combination of these two: either (1) the surgeon capabilities (dexterity and system knowledge) are limited for proper control of the system, or (2) the system has suboptimal conditions that present limitations for a proper control to reach the desired end result. Improvement of the surgical lighting system is necessary, since the OR light is an important aspect during the surgical procedures. In order to provide a solution for the interaction, one needs to improve the knowledge of the user, the functioning of the system, or both.

The thesis is needed to gain insight into the research problem. The scope or solution of the OR lighting problem is not at hand due to limited insights. The available research papers only point out the problem, but do not describe the scope or solution of the problem. A description is only accomplished by an observation of the interaction between the user and SLS during surgical procedures.

An observation can accomplish a description of the interaction between surgeon (user) and the SLS and to detect and quantify problems of perioperative luminaire usage. To rule out the surgeons own incapability's that affect his perception, an observation gives a more objective insight. Furthermore, the limitations of the surgeons are beyond the scope of this dissertation. This dissertation is from an engineering point of view. Engineering is the science of acquiring and applying technical knowledge to design systems, therefore the primary focus is the exploration of the sub-optimal conditions of the lighting system.

2.5 Conclusion

This chapter has described the current state of information of the OR lighting problem. The problem is a perception of a deficient interaction between a medical staff member and the SLS to reach the desired result. Therefore the OR lighting problem is in fact a control issue during a user system interaction. Due to limited insights, the scope or solution of the control problem is not at hand. The available papers only state the surgeon's perception of the problem. An observation of the interaction between the medical staff and the SLS during surgical procedures is necessary to gain the required insights.

3. Observation method of the surgical procedure

3.1 Introduction

This chapter is aimed at the second research question of how the interaction between the surgeon and surgical lighting system during a surgical procedure can effectively be illustrated. Paragraph 3.2 states the explanation and justification of the research methodology and method. In Paragraph 3.3 the focus of the observation study is given followed by Paragraph 3.4 in which the observation instrument is presented by three stages: the sample characteristics; the collected data and the recording method. Paragraph 3.5 states the data analysis technique, followed by the validity en reliability of the research in Paragraph 3.6. The final Paragraph 3.7 states the conclusions of this chapter.

3.2 Explanation and justification of the research methodology and method

In this research qualitative methodology was used. Qualitative research is concerned with non-statistical data collection of phenomena in their natural setting, for the purpose of gathering an in-depth understanding of human behaviour and the reasons that govern such behaviour [8]. Qualitative research usually begins with an intention to explore a particular area, collects "data" and generates ideas and hypotheses from these data largely through what is known as inductive reasoning [17]. Qualitative research can thus be broadly described as interpretative and naturalistic. In that it seeks to understand and explain beliefs and behaviours within the context that they occur [9].

Instead of aiming at accepting or rejecting an a priori defined hypothesis in quantitative strategies, a qualitative research approach is aimed at constructing a theoretical framework that emerges from the analysis of the data gathered during the research and enables to explain the research results in a coherent manner. Such a framework is called a grounded theory [11]: “Generating a theory from data means that most hypotheses and concepts not only come from the data, but are systematically worked out in relation to the data during the course of the research.” [11].

This research has adopted qualitative methodology and the observation method. Qualitative research is selected due to the fact that no records of previous studies exist, as stated in chapter two, and therefore this dissertation aims to construct a theoretical framework. Qualitative research is associated with a number of different approaches to data collecting, but these approaches mostly fall into the categories of interviews, and observations [9].[2] The dissertation scientific research question aims to effectively illustrate the interaction between user (surgeon) and system (surgical lighting system) during a surgical procedure. The observation method is a technique to establish the human behaviour and the dynamics of one’s profession. The observation method is a direct and valid method of research to obtain factual data because the resulting data is derived from people’s actions, rather than their interpretations [10].

The selected type of research method is a non-participant direct observation study. There are two types of observation techniques: Participant or non-participant [1]. In participant observation the data is collected by interacting with, and therefore experiencing, the phenomenon being studied. In a non-participant observation the data is collected without taking active part in the situation in scrutiny [1]. For the research in this dissertation a participant study was simply ethically not possible since the researcher is not medically schooled.

The selected approach was the semi-structured, non-participant direct observation. There are three approaches possible with the observation method; (1) unstructured or open, (2) semi-structured and (3) structured observation [1, 2, 10]. A structured observation is too strict for this explorative dissertation, since it requires that the desired behaviours must be explicitly defined so that there is no question in the mind of the observer as to whether or not they occur. On the other hand, an open observation is deemed to result into unreliable data due to its extensive and widespread approach of data collecting. The semi-

[2] Other qualitative research tools exist for data gathering in addition to observations and interviews, such as researcher diary, reflections, questionnaires, artefacts and documents [12].

structured gives reliable insights due to a pre-defined datasheet, while still maintaining flexibility by allowing new insights to be brought up during the observation as a result of what is observed.

3.3 Focus on routine surgical procedures in the field of general surgery

This research focused on the OR lighting problem during routine invasive surgical procedures in the field of general surgery. The observation study was carried out at the Reinier de Graaf Gasthuis hospital in Delft, a large non-university teaching hospital. The surgical procedures were selected with a surgeon for both their routine nature and likeliness for luminary actions.

There is a range of hospitals, SLS brands, and categories of surgical procedures within all various medical disciplines, of which not all are either suitable or obligatory to study in this research. From this perspective it was deemed necessary to use a selection procedure in order to determine the data sample that will fulfil the scientific and practical requirements. In the section below the selection process is described to establish this data sample.

The primary scientific selection criteria were the certifications that the research is optimally valid and reliable, so that the observation data correspond as best possible with the reality based on the relevant data (the user system interaction). In order to aim for efficient observation time, the characteristics of the surgical procedures would preferably have a high possibility of influencing the interaction between the user (surgeon), and the luminairy system variables. With the application of the scientific criteria the data sample was restricted to invasive surgical procedures, and eliminates the laparoscopic and non-invasive surgical procedures. These last two types were beyond the scope of this research since the identified problems only occur during invasive procedures [22]. Laparoscopic and invasive surgeries both have completely different ways of lighting the operation field and as a result different OR surgical lighting systems. Invasive surgery uses a luminaire that is suspended by the ceiling, and in minimal invasive surgery the luminaire is placed inside the patient's body and the patient tissue is viewed indirectly with a camera. In each type of surgical procedure the surgeon experiences OR lighting problems. In this stage of exploration of the identified problems, the invasive surgery was selected for this dissertation, since it has better accessibility in the observation method.

Next the practical restrictions were considered. The non-participant study takes places in a fragile environment that is vulnerable to risks of safety hazards. The safety of the patient is the main priority, which also requires the cooperation of the surgeon; the presence of the observer in the operating room must not negatively affect the outcome of the surgical procedure. The identified safety elements to consider are risk of (wound) infection, low demands on air flow disturbance, the procedures emergency level and minimal negative influence on the surgeon's level of concentration. Under the assumption that a correct application of the practical selection criteria requires medical experience, the final selection was made in consult with a surgeon. The field of general surgery, in combination with routine surgical procedure, was deemed as the most compliant for the observation study, Within general surgery, most procedures have relatively low risk of sterile infection, and routine operation (instead of trauma surgery) reduces the safety hazards further due to the lower complexity .

The selected data sample was considered to suffice the scientific and practical criteria. There was no reason to assume that the nature of the surgeons control problem with the surgical lighting system depends on the surgical field or emergency level of the surgical procedures. Within invasive surgery, all SLS have in general the same variables [18, 20]. In addition, it is likely that high risk and stressful procedures amplify the surgeon's (or medical staff's) demands on the system, but do not change the specific requirements. As a result, this stressful situation only increases the intensity and not the nature of the control problem.

3.4 The observation instrument

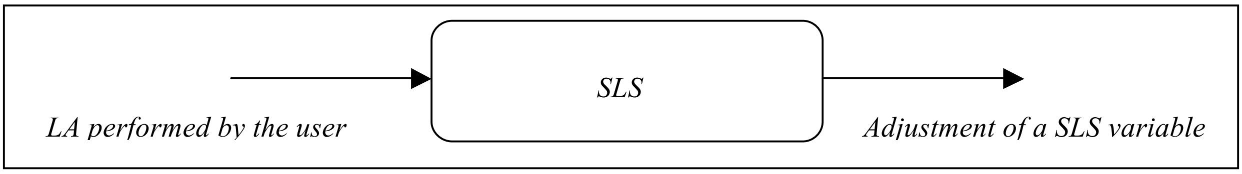
The basic inclusion for this study was that only information was recorded which was necessary to describe the interaction between the user and system during surgical procedures. Only that information is relevant for the research goals. With that basic principle in mind, the following steps were undertaken.

The description of the observation instrument is divided into three parts. The first part describes the inventory of the relevant information by identifying and structuring the observation variables (c.f. 3.4.1), after which the second part shows how the data was collected during the implementation of the observation (c.f. 3.4.2). The last part presents the characteristics of the data sample (c.f. 3.4.3).

3.4.1 Inventory phase: Characteristics of the user-system interaction

The observation study was seen as a causality study, investigating the interaction between the user and system as an input & output system (Fig. 22) on the timeline of the duration of a surgical procedure. The input variable is the action performed by the user on the luminairy system. The output variable is the change of the SLS caused by the action.

Figure 22 - Block diagram of the user system interaction during surgical procedures.



In this study the user-system interaction was viewed as an input-output system; the luminairy action is the input of the interaction which results in the output of an adjustment of an SLS variable.

Input variable: the luminairy action.
During the surgical procedure all SLS-related actions of the medical staff were recorded. An action, which results into a SLS variable adjustment, was referred to as a *luminairy action (further: LA)*. The member of the medical staff who undertook the action was referred to as the *luminairy performer (further: LP)*. It was assumed that the luminairy action can lead to an imperfect adjustment of the system variable, in which case the performer has to make a correction adjustment. A LA was therefore qualified as either a manipulation or correction.

Of the four members of the surgical team (cf. 2.2) only the surgeon and assistant surgeon perform the surgical actions, but either can also perform supporting actions. To identify each role the following distinctness can be made: if either of these performs a surgical activity, that is not intended to control bleeding, suturing or provide wound exposure, they were referred to as the *medical operator (further: MO).*

The LP was asked to explain the motivation for the LA. There are multiple motives for a medical staff member to perform an LA [6]: Change of the work area of the surgical activity; change of point of view medical operators; no illumination / shadow in the work space; no contrast in the work space tissue; bright light; light reflection on tissue or surgical instruments; out of focus work area for instance due to the repositioning of the table or the patient.

Output variables: the SLS variables.

The Reinier de Graaf Gasthuis hospital employs the SLS of brand Berchtold and type C series (Fig. 23). It appears that all SLSs in general have the same fundamental design that defines the scope of user system interaction [18, 20].

Figure 23 - SLS of brand Berchtold and type C

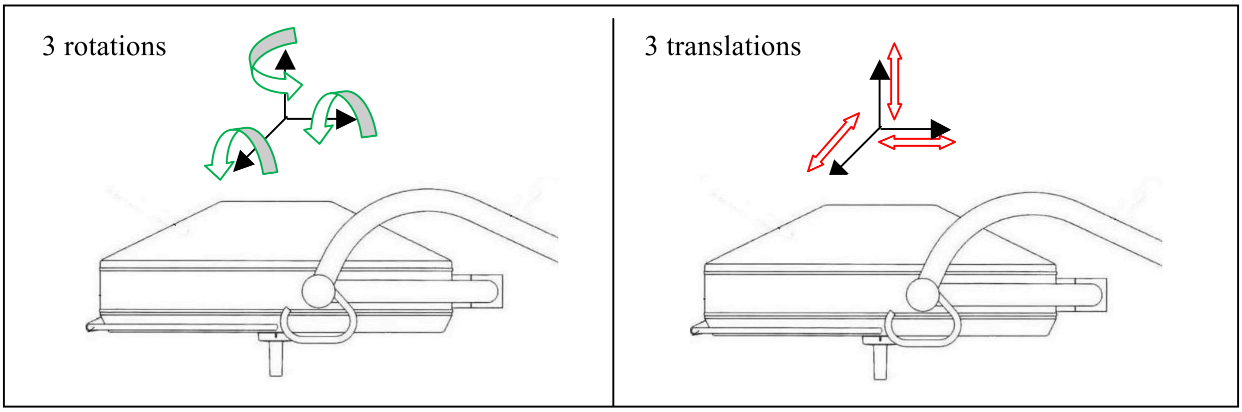
Both the main and auxiliary luminaire have same three variables that require different control actions. The SLS on/off button was omitted as a system variable, since this variable is not changed during surgical procedures:

(1a) An adjustable *focus*, which affects the size of the diameter of illuminated field;

(1b) An adjustable *illumination level*, which affects the intensity of the light beam;

(2) Five degrees-of-freedom which affect the *position & orientation* of the *luminaire*: 3 translations of the luminaire, 2 rotations of the luminaire. In addition, the luminaire can rotate, as the whole SLS, around its central axis in the ceiling mount. In that configuration the system loses one the translational direction, since the pendant arms are in parallel configuration (Fig. 24).

Figure 24 - Pictorial representation to explain the possible rotations and translation of the luminaire.



The surgical lighting system has five degrees of freedom, but the luminaire has three rotations (left picture) and three translations (right picture) [4]. For the rotation of the complete SLS around its central axis in the ceiling mount, the system loses a degree of freedom, since the pendant arms are in parallel configuration.

The Variables 1A and 1B below are changed via buttons on the system and require an intuitive interpretation or knowledge of the systems interface (Fig. 25). Variable 2 is controlled via the luminaire handle, and requires that the user has an intuitive sense of the systems mechanics (Fig. 26).

Figure 25 - The interface of a surgical lighting system.

The buttons need to pressed to change the Variables 1A & 1B [4].

Figure 26 - The luminaire handle.

The handle is used by the medical staff to change system Variable 2.

Besides the input and output characteristics, there are extraneous variables which were beforehand assumed as relevant data that will give further insight into scope of the user system interaction:

- Duration of the surgical procedure from initializing until finalizing phase; Number of LAs during the surgical procedure; phase of the surgical procedure at time of LA (cf. 2.2); time duration of the LA, which was initially defined as the moment that the LP initiates an activity of the upper extremities to begin the LA and ends as the LP continues his original task;
- Function of the performer (LP) of the LA; whether LP is also the medical operator (MO), in combination of the operation activity during the performance of the luminairy action (cf. 3.4.1 and 2.2); posture of the LP: standing or sitting; focus of the LP throughout the LA;
- Number of LPs required to perform a LA; relocation during LA was one- or two-handed; visible ease of LA, which is divided (1) whether the luminaire relocations takes place along the shortest route in 3D space, or (2) a LA is 'non smooth' if the performer had to apply full force or undertake a oscillating action to start the movement; and,
- Any additional comments.

3.4.2 Data recording

Rationale behind the data recording during the non-participant observation was to use a minimal set of equipment. This was due to the hospitals request to limit the influence of the observation on the process of the surgical procedure. For instance due to non-sterile risks, obstructing the work space and routine of the medical staff or negatively influence the staff's concentration by the employed materials and method of this study.

This approach resulted in two different stages of data recording and consequently in two datasets. The first dataset was recorded using a score list and definition sheet (see Appendices B and C for the observation score list and definition sheet), and a stop watch for time recordings. The second dataset was recorded with the same score list and definition sheet, but the time recordings were carried out with a video camera.

Video recordings enable repeated viewing, which makes the time recording of the LA more controllable and therefore more reliable then the stopwatch recordings. The accuracy of the stopwatch approach was primarily influenced by the researcher's reaction time. This led to partially or even missed action duration recordings. All the time recordings of the LA by stopwatch were, therefore, ignored in this thesis.

3.4.3 Data sample characteristics

The observation study was carried out at the Reinier de Graaf Gasthuis hospital in Delft. Observations were done in two ORs having the same SLS consisting of a large main luminaire (Berchtold Chromophare C950, Berchtold, Charleston, SC, USA) and a small auxiliary luminaire (Berchtold Chromophare D530 plus).

The total data sample consists of 14 routine surgical procedures within general surgery, with a total duration of 45 hours and 8 minutes. Some procedures included multiple wound locations at different locations of the body, some had large wound areas and others had narrow and deep wounds. The surgical procedures were from various sub-disciplines (Table 6).

The recording technique resulted into two datasets which were viewed as a primary dataset with a subdataset: The total dataset of N = 364 activities, consisted of the collected data by the score list. The sub-dataset of N = 249 (of the N= 364 dataset) consisted of the data collected with the use of a video camera. Only the sub-dataset contains accurate LA time durations.

Table 6- The characteristic of the data sample of the observation study.

Type of surgery	Gastrointestinal	Vascular	Breast	Thyroid gland
Number of observed procedures	6	2	4	2

The data sample is presented as the number of surgical procedures allocated by the disciplines within the field of general surgery. The study contained 14 surgical procedures in four types of sub-disciplines. Gastrointestinal surgery is surgery on the human digestive system and vascular surgery is surgery on arteries and veins.

During the surgical procedures both the anaesthetic and the surgical team were always present. The surgical team consisted of four or five members, since during certain stages of the surgical procedures two surgeons could be present besides the assistant surgeon, the first assistant and the circulating nurse.

3.5 Data analysis

This research employed the interpretive technique for the data analysis, which is an analysis by the observer's impression. The observer, seen as an engineering expert, examines the data and interprets them via forming an impression and report the impression in a structured and sometimes quantitative form.

This dissertation is an explorative study, not the more frequent hypothetico-deductive research and was therefore not aimed at accepting or rejecting an a priori defined hypothesis. As a consequence, it was not possible to define a specific data analysis technique prior to the data collection. By means of the preceding mentioned variables (cf. 3.4) a data analysis was accomplished to obtain the nature and scope of the OR SLS problem.

3.6 Validity, reliability and generalization of the observation method

Threat to internal validity was the bias due to observation transfer. The researcher was a non-participant observant, and transferred his interpretations of whether the user system interaction is a problem. This lead to the primary limitation of this study: an objective approach is used to gain insight into the subjective problem. The medical staff member classifies the interaction with the SLS as problematic in his perception, but their interpretations were not included in this study. Therefore it can be possible that the subjective problem is greater or smaller than the insight gained from this research. This limitation depends on the degree to which the interpretation of a problematic interaction has mutual meanings between observed and observer. To enhance internal validity this study aimed to obtain as much quantitative data as possible based on the definitions that are given to the interaction variables in Paragraph 3.4 and the definition list (Appendix B).

In addition the observer paradox has to be taken into account. The presence of the observer during the surgical procedures might influence the behaviour of the medical staff members which in turn affects the user system interaction. This limitation will be diminished by being present during multiple surgical procedures.

Generalization conclusions cannot be drawn based on the observation study, since the data sample consist of only one hospital, one SLS and limited number of procedures were included. Conclusions can only be drawn for the surgical procedures in the data sample at the Reinier de Graaf Gasthuis hospital with a SLS of the brand Berchtold and type C series. However, from the available research papers with insight from surgeons of other hospitals it is known that the OR light problem takes place on a wider scale. The selection criteria of the data sample presumably only influence the intensity and not the nature of the problem, while all SLS in general have the same interaction variables. So, from a qualitative perspective, the external validity will be primarily the responsibility of the reader and not the researcher.

Threat to the reliability was the researcher bias due to scientist's own involvement and role within the study as an observer. The sole observer who is not a medical specialist interpreted the self-collected data which might have affected the reliability of the study. To increase the reliability of the data sample, and ensure that another researcher would come to the same conclusion in repetition, the data collection method has been described in detail and recorded as described in Paragraphs 3.3 & 3.4 in combination with a score list and definition sheet that were defined before the observation study to increase objective data collection (Appendices B and C).

3.7 Conclusion

This research used the observation method to effectively illustrate the interaction between user (medical staff member) and the SLS during a surgical procedure. This research method is part of the qualitative research methodology. The observation study was seen as a causality study, investigating the interaction between the user and system as an input & output system on the timeline duration of a surgical procedure. The input variable was the action performed by the user on the SLS. The output variable was the change of the SLS caused by the action. The data was collected during open routine surgical procedures in the field of general surgery. The location of the observation study was the Reinier de Graaf Gasthuis hospital in Delft, which employs the Berchtold C series as the SLS.

4. Analysis of the observation results

4.1 Introduction

In this chapter the results of the observation study are presented, aimed at the third and fourth research questions: Describe the scope of the OR lighting problem during surgical procedures; and define the two primary criteria how the use of the surgical lighting system can be improved. The observation was performed to illustrate the interaction between the user and the system during surgical procedures. Paragraph 4.2 states the data sample characteristics, followed by Paragraph 4.3 which gives the analysis of the characteristics of the recorded variables. Paragraph 4.4 focuses on the mechanical configuration of the SLS and Paragraph 4.5 states the conclusions of the observation research.

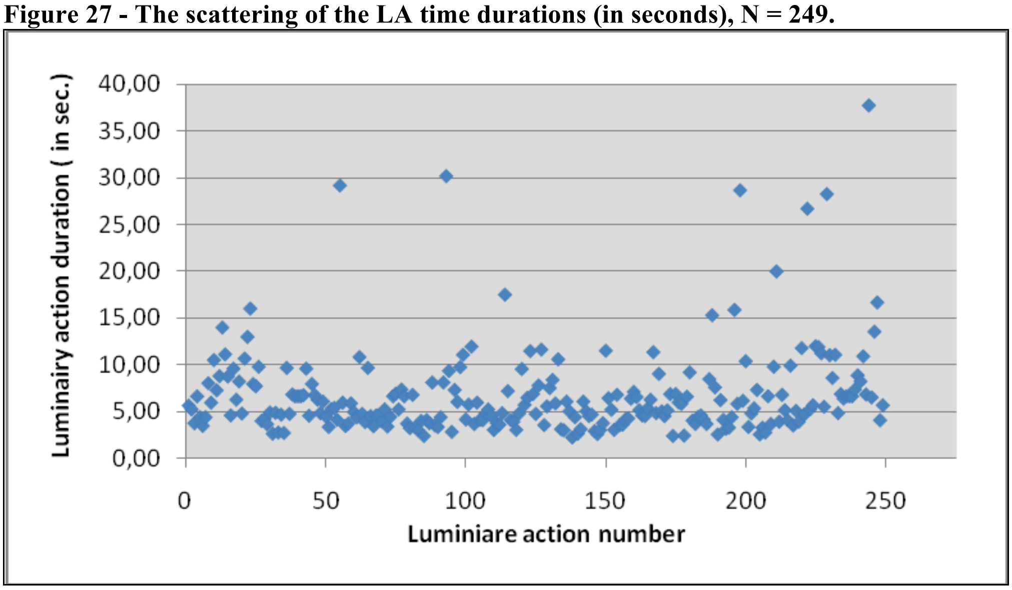
4.2 Data sample characteristics

This Paragraph briefly states the sample characteristics, since the previous chapter already described the data sample. The data are presented below as a descriptive statistics of unprocessed tangible data by expressing the main features of the sample in quantitative terms.

The total data sample consisted of 14 routine surgical procedures within general surgery, with a total duration of 45 hours and 8 minutes. The total dataset consisted of N = 364 luminairy actions collected data by the score list. A sub-dataset of N = 249 (of the N= 364 dataset) consists of the data collected with the use of a video camera. As a result, only the sub-dataset contains accurate action durations. The second data set was able to present reliable duration recording of the luminairy action.

The unprocessed data of the luminairy action duration of the dataset N = 249 have a non-uniform scattering of LA time duration (Fig. 27). The extreme time durations of the observed LA were between 37.7 seconds as the longest and 2.2 seconds as the shortest.

Figure 27 - The scattering of the LA time durations (in seconds), N = 249.



The scattering of the LA time durations in the data sample illustrates extreme time duration between 37.7 seconds as the longest and 2.2 seconds as the shortest.

4.3 Results of the observation instrument

The analysed observation data is presented in two stages; first the characteristics of the user system interaction and LA are described, followed by the identified complications.

4.3.1 Characteristics of the user and SLS interaction

During the observed 45 hours and 8 minutes of surgery, in total (N =) 364 LAs were noticed, resulting in an average period of one LA every 7.4 minutes. All those LAs were identified as repositioning actions of the luminaire. The light beam's focus and the illumination levels were never adapted during the observation period.

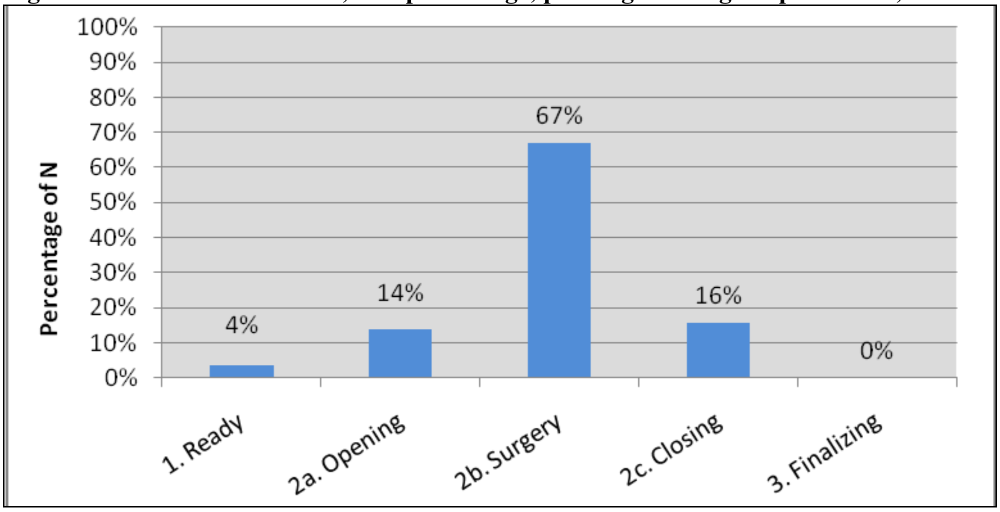
The dominant observed motive for the LA was the 'change of work area of the surgical activity' (97 %), followed by a 'change of viewpoint of the medical operator' (6%), and low visibility due to 'shadow on work area' (2%), (Table 7). The two observed LAs due to the reason "out of focus work area" occurred after a repositioning of the operation table.

Table 7 - The perceive motives of the medical staff member to perform a LA, N = 364.

Motivation for the luminairy action	*Number of actions*
1. Change of work area of surgical activity	333
2. Change of viewpoint medical operator	21
3. Shadow on work area	8
4. Out of focus work area	2
Total	*364*

Figure 28 displays the stage of surgical procedure in which the LA was observed. Most of the LAs took place in phase 2b (67%), which is the complex stage of the surgical operation to carry out the objective of the surgical procedure in the wound. During the opening and closing of the wound 30% of the LAs were performed, mainly because knife or the needle driver were followed with the light pattern when progressing along the line of incision.

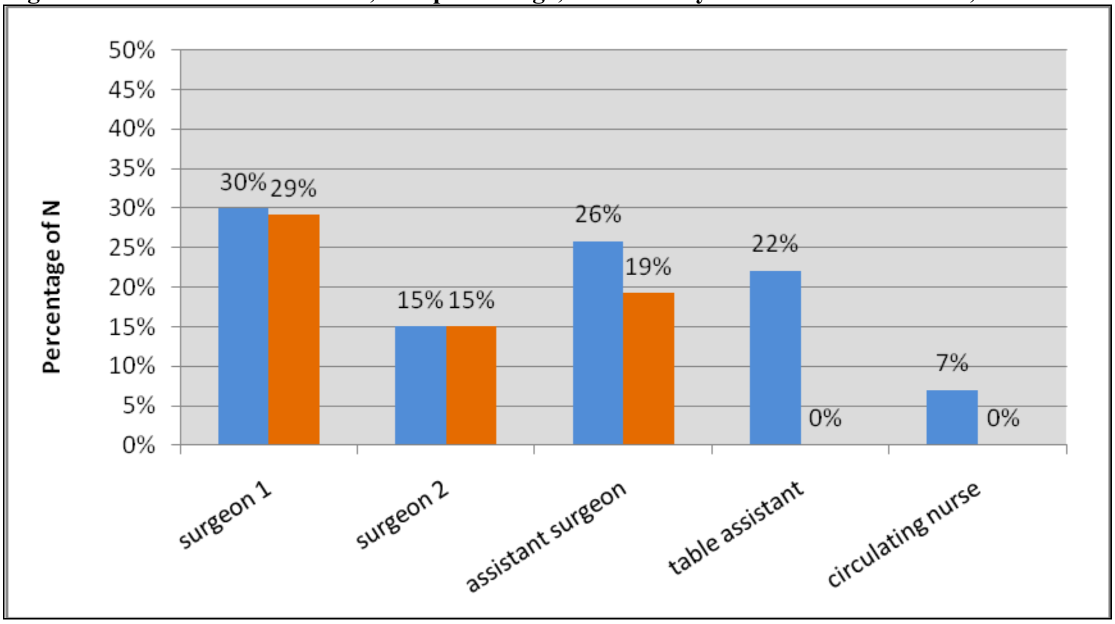
Figure 28 - The observed LAs, as a percentage, per stage of surgical procedure, N = 364.



The stages of the surgical procedure were defined in Paragraph 2.2, page 40. Most of the LAs were observed during the complex stage of the surgical procedure

Surgeons performed 45% of all the observed LAs (Fig. 29). In 97% they had to interrupt their surgical tasks to do the LA. So the principal staff member responsible for the successful outcome of the surgical procedure is also the primary LP of the LA. Assistant surgeons took 26% of the LAs, during which they had to interrupt their surgical tasks in 73% of the cases, followed by the table assistant (22% - 0% interrupting surgical tasks) and the circulating nurse (7% - 0% interrupting surgical tasks). In total, 68% of all the LA during the phase of surgery (Sub-phase 2a, 2b and 2c of figure 10, N = 351) interrupted surgical tasks to reposition the luminaire. Figure 10 shows which medical staff member performed the LAs during the observed surgical procedures as a percentage of the total number of observed LAs. The brown coloured rows depict the percentage of all 364 actions in which a medical staff member is the LA performer as well as the medical operator.

Figure 29 - Performer of the LA, as a percentage, classified by function staff member, N = 364.



The medical staff member that was the performer of the LA during the observation study is presented in the blue colour bar. Also, in the brown colour bar, is presented the percentage when the performer of the LA was also the medical operator, N = 364. Surgeons performed 45% of all the observed LAs. In 97% they had to interrupt their surgical tasks to do the LA.

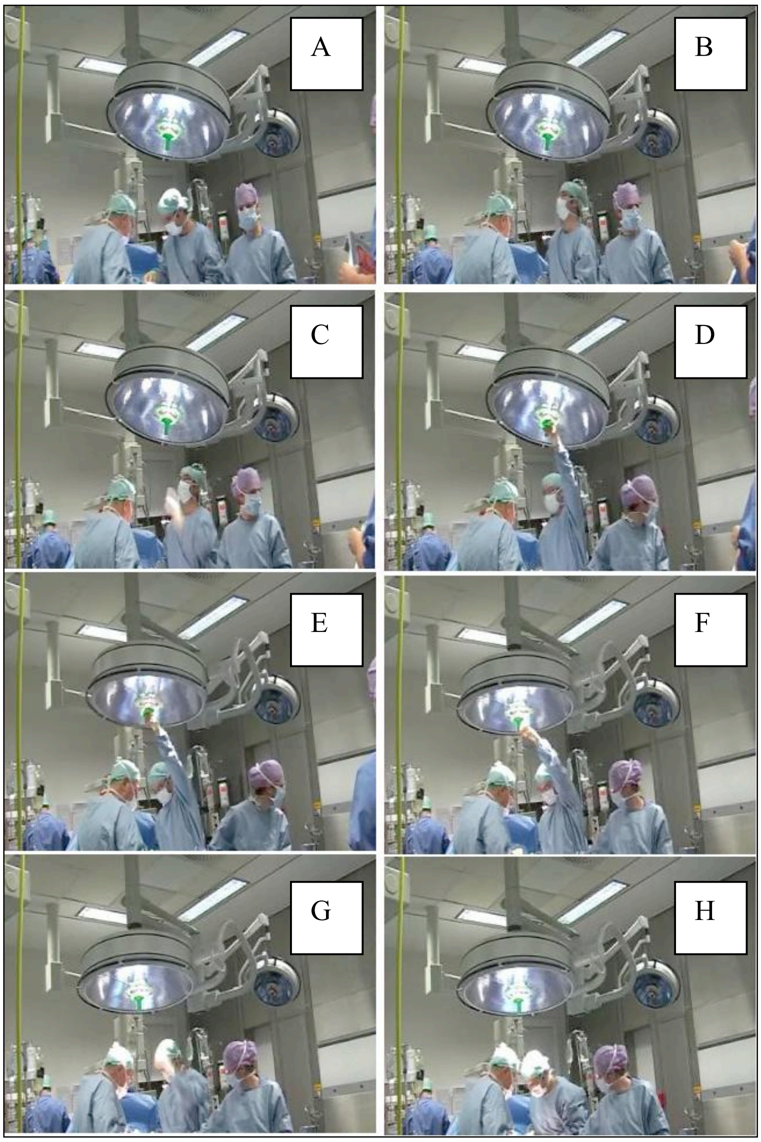
The video recorded LAs (N = 249 LAs) could be analysed more extensively afterwards. The analysis showed that the user SLS interaction of an LA proceeded along a cyclic pattern of activities. The pattern of the cycle entailed 5 succeeding stages between an initial and end condition (Fig. 30):

I. The initial condition: The medical staff member is in his/her initial posture [A];
   1. The medical staff member, now called the performer, initiates a head movement to establish visual contact with the luminairy system [B];
   2. The performer initiates a movement of the arms (upper extremities) in order to reach the luminairy system [C];
   3. The performer establishes physical contact by grasping the lamp handle [D];
   4. The performer repositions the lamp [E];
   5. After which the performer releases the lamp handle and the physical contact ends. The performer returns to a posture similar to the initial condition [F];

II. End condition: The medical staff member is back to his/her initial posture [G].

A LA from stages A till G were labelled as the *LA cycle*, in which stages D & E form the *pure LA*, in which there was direct contact between performer and SLS.

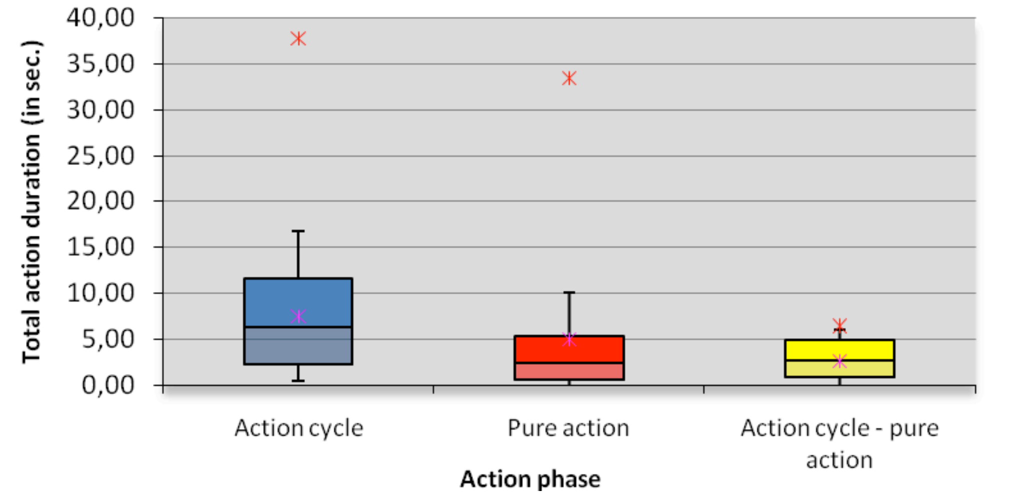
Figure 30 - The repetitive pattern of the LA, N = 249.



The repetitive pattern of the observed LA: the action pattern was a cycle that underwent five stages between the initial condition at stage A and the end condition at stage H. The various stages are described in the text on the previous page 52.

The overall LA cycle had the median time duration of 5.4 seconds. Fig. 31 shows the boxplot of the various LA time durations. A frame by frame video analysis of the recorded data together with the defined cyclic pattern stages allowed this accurate representation of the LA time durations. The pure LAs had a median of 3.0 seconds (stage D-E-F). It took a median of 2.2 seconds for the LA performer to move to or from the OR luminaire (stages C-D & F-G).

Figure 31 - The median time duration of three stages of the LA, N = 249.



The time durations of the luminairy action stages, N = 249. These stage were defined in Paragraph 4.3.1 page 52. An action cycle has a median time duration of 5.4 sec., a pure action 3.0 sec., and the time duration between action cycle and pure action 2.2 sec

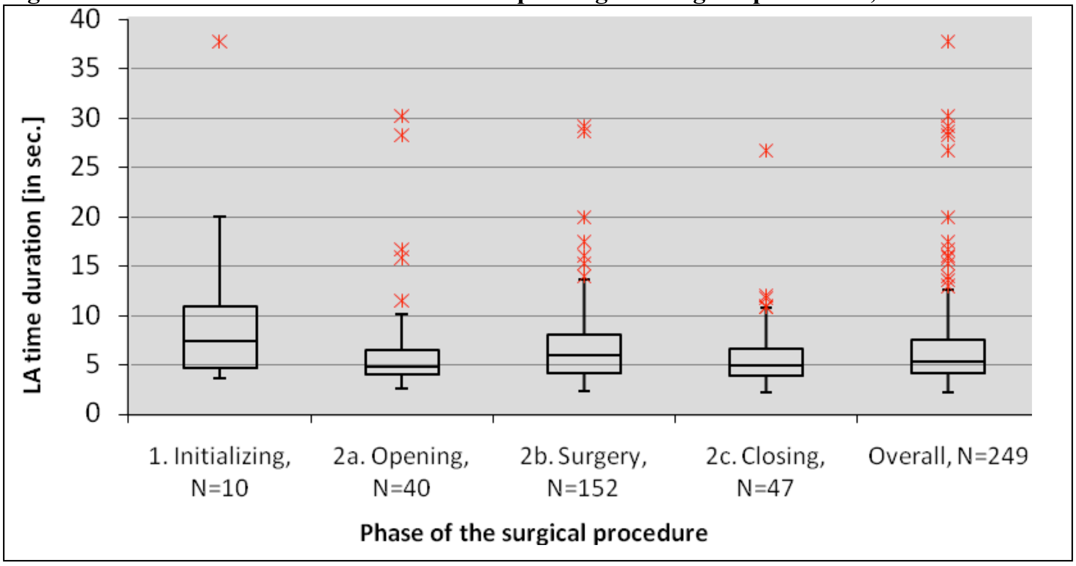
In addition to the given figure and tables, some noteworthy findings of the user system interaction in the total data sample of the score list were:

- The performer was almost always in a standing posture at the time of the LA. In 10 of N = 364 LAs of N = 364 the performer was in a sitting posture. During those 10 LAs the performer was also the medical operator;
- Almost all LAs were executed by the performer using one hand. In 18 of N = 364 LAs the performer used both hands to adjust the systems directionality;
- In 8 of the N = 364 LAs the directionality adjustment was undertaken by two performers;
- 10 of the N = 364 LAs were qualified as a correction LA, as the performer corrected the initial manipulation LA to adjust the directionality adjustment of the luminary system;
- In 345 times of the N = 364 activities the LA was performed on the main luminaire of the SLS.

4.3.2 Difficulties during the user - SLS interaction

Outliers in the median LA durations - overall and per phase of the surgical procedure – indicate the most problematic adaptations of the SLS (Fig. 32). Clearly, most difficulties occurred during surgery phase's 2a-2c (c.f. Paragraph 2.2) where they have the highest impact on the distraction of the surgical staff.

Figure 32 - Median time durations of the LA per stage of surgical procedure, N = 249.



The time durations of the observed LAs per stage of the surgical procedure shows outliers. These indicate the most problematic adaptations of the SLS. Clearly, most difficulties occurred during the surgery phase 2a-2c (cf. Paragraph 2.2).

The prominent difficulty during the user system interaction, resulting in extreme LA time durations, was an occurrence labelled as 'mechanical singularity of the luminairy system' (Table 8), which is more or less a gimbal lock[3] of the SLS two pendant arms. A pictorial presentation of such an occurrence during the observation study is given on the next page (Fig. 33) after which the situation is analysed later on. During all the LAs the LP at a time is fully visually focused on the SLS and therefore looses contact with the operational field.

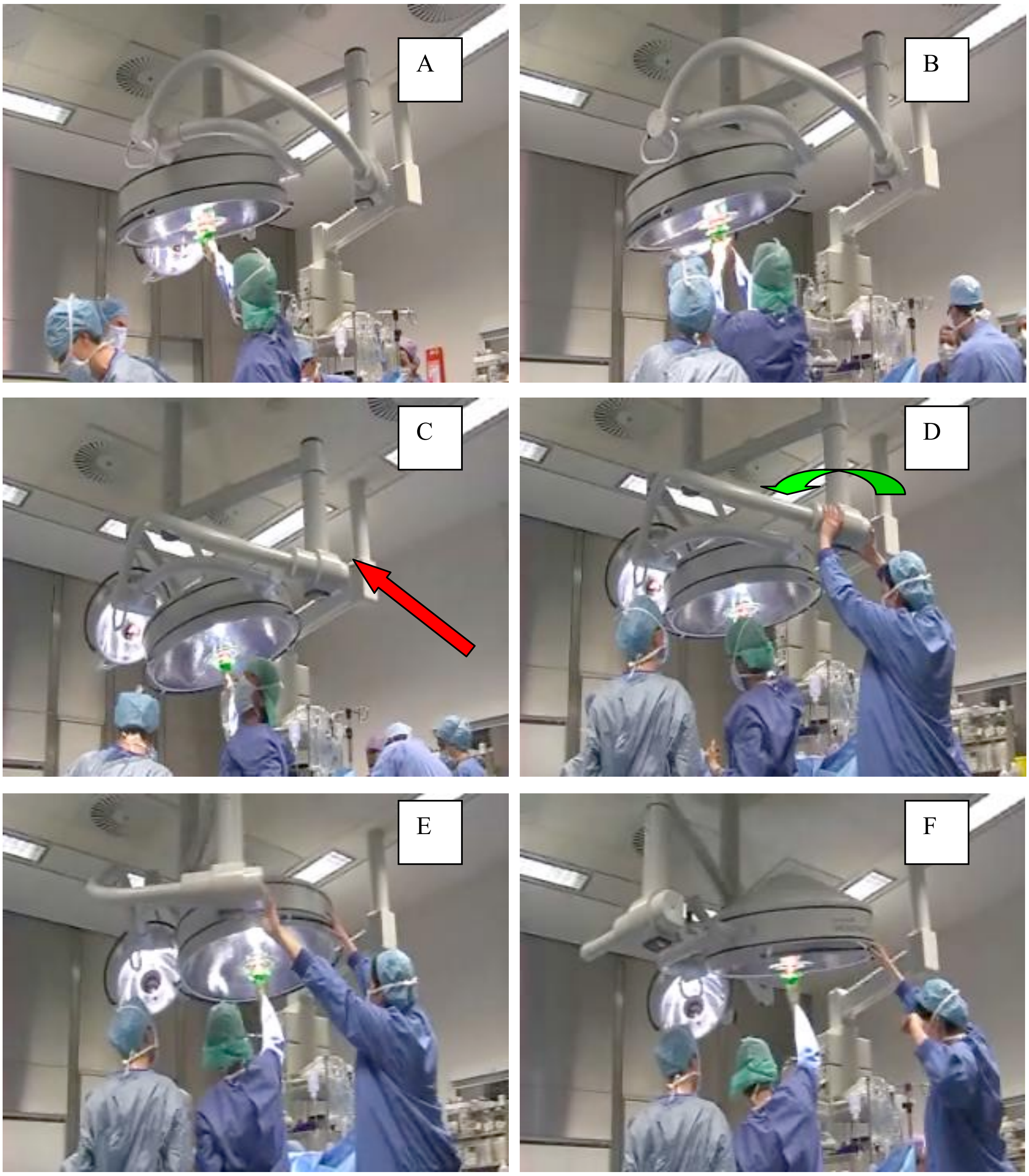
Table 8 - The identified reasons for the exceptionally long time durations of several LA cycles.

Action number	*Action duration (sec)*	*Reason for long action cycle*
244	37,8	Luminaire does not rotate due to obstruction, reconfiguration necessary
93	30,2	Relocation luminaire (satellite) along a long path length
55	29,2	Performer cannot relocate system along desired route, due to mechanical singularity of the luminairy system.
198	28,7	Location luminaire handle is out of reach seated performers' reach
229	28,3	Location luminaire handle is out of range of the seated performers reach
222	26,7	Medical device in OR form obstructions in pathway luminaire
211	20	Performer cannot relocate system along desired route, due to mechanical singularity of the luminairy system.
247	16,7	Performer cannot relocate system along desired route, due to mechanical singularity of the luminairy system.
23	16	Performer cannot relocate system along desired route, due to approximate mechanical singularity of the luminairy system.
114	17,5	Performer keeps slightly repositioning luminaire without any surgical activity
196	15,9	Relocation luminaire (satellite) along long path length
188	15,3	Temporary halt in relocation after collision between system & human

The reasons for a long LA action cycle are arranged in order of the LA time duration, and adjoined with the action number of the dataset.

[3] A gimbal lock is the loss of one degree of freedom that occurs when the axes of two of the three gimbals are driven into the same place and cannot compensate for rotations around one axis in three dimensional space.

Figure 33 - Pictorial presentation of a 'mechanical singularity' (gimbal lock) of the SLS during a LA.



7. **The medical staff member, as the performer, initiates a one handed luminairy action (LA) to reposition the luminaire [A];**
8. **The LP is unable to reposition the lamp by one hand and uses two hands to produce extra force on the luminaire [B];**
9. **The LP is still unable the reposition the luminaire in the preferred direction, which coincides with the parallel pendant system arms (indicated with the red arrow), resulting in a loss of degree of freedom. [C];**
10. **A second medical staff members is required to assist the LP with the LA, by rotating the pendant arms (indicated with the green arrow) [D];**
11. **The second medical staff member rotates the parallel system arm in a direction that is unequal to the direction preferred by the performer [E]; and**
12. **The prior LP is able the reposition the luminaire in the preferred position to complete the LA [F].**

The SLS was illustrated as a free body diagram to analyse the forces during the occurrence of mechanical singularity (Fig. 34). The employment of Newton's second law is presented in equation 1; a force is applied by the user ($F_{applied}$) on the luminaire at distance (L) from the joint to initiate the LA. $F_{applied}$ has to overcome the two reaction joint friction moments, divided by L (($M_{friction\_1}$ & $M_{friction\_2}$)/L) to generate a luminaire reposition in the plane of the desired motion. But when the SLS pendant arms are (almost) in parallel alignment the moment arm (L) reaches zero. As a consequence, the applied force ($F_{applied}$) can reach infinity without causing any luminaire motion. This mechanical singularity will also occur when the pendant arms are in serial alignment.

If the LA entails a 2D translational reposition of the luminaire, it is hypothesized that the required force to induce a luminaire reposition has a peak magnitude (Fig. 35) when the pendant arms are in parallel or serial alignment.

Equation 1 - Application Newton second's law on SLS

$$\sum \left(M_{luminairy\_action}\right)_A = 0 \text{ when there is no rotational motion.}$$

$$\left(F_{applied} \cdot L - M_{friction\_1} - M_{friction\_2}\right)_A = 0$$

$$\rightarrow$$

$$F_{applied} = \left(M_{friction\_1} - M_{friction\_2}\right) / L$$

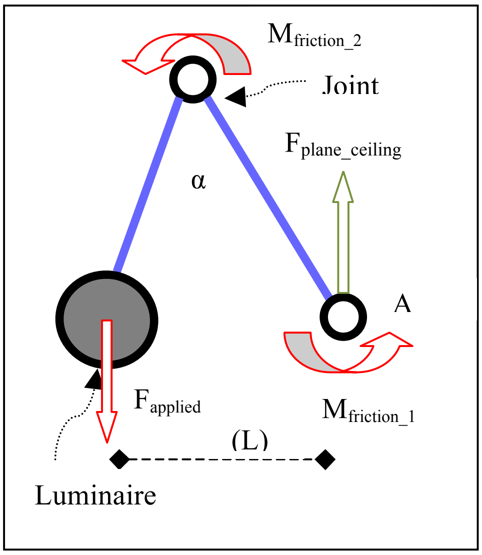
$$\text{if } L \cong 0 \text{ then } \lim_{L \to 0} \left(M_{friction\_1} - M_{friction\_2}\right) / L$$

$$= \lim_{L \to 0} F_{applied}(L) = \infty$$

So if L nears zero, $F_{applied}$ reaches infinity

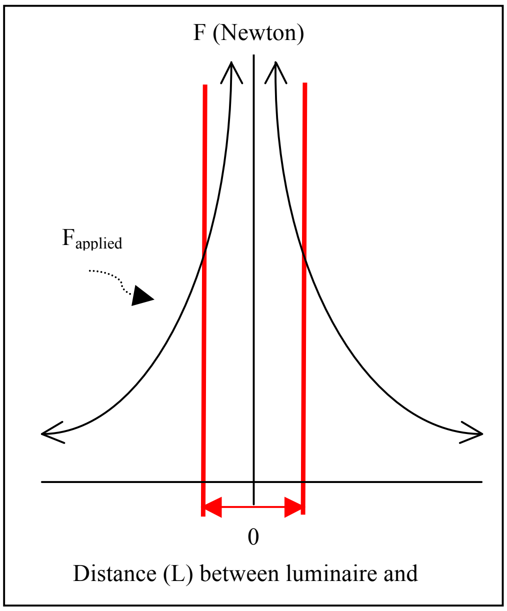
The application of Newton's second law equation on the free body diagram of the SLS (Fig. 34. If L reaches zero, $F_{applied}$ reaches an infinity quantity.

Figure 34 - 2D free body diagram of SLS luminaire and pendant arms.



The 2D free body diagram is in plane of the ceiling, and shows a top view of the surgical lighting system with the forces to induce a translational repositioning of the luminaire.

Figure 35 - Hypothesized force distribution.



The hypothesized force distribution (Eq. 1 and Fig. 34), to induce a 2D translational reposition of luminaire through a parallel pendant arm configuration, will have a peak force when L ± 0.

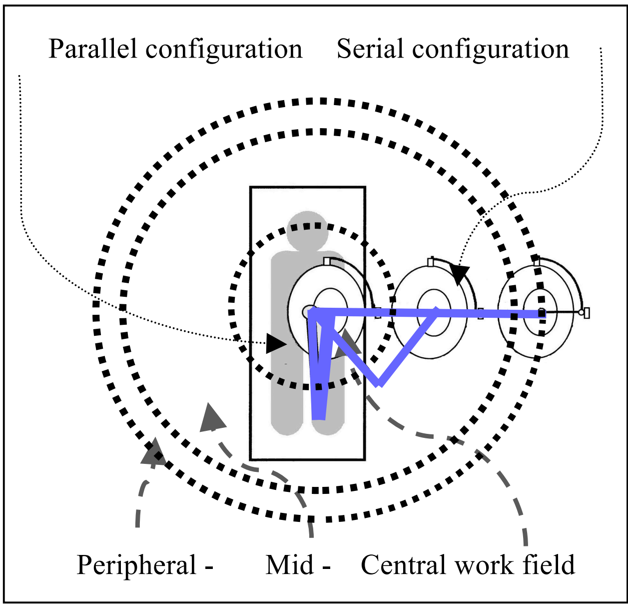
In total 24 events of these significant mechanical difficulties were witnessed during the observational study, with various sources. During these events the concentration of the MO appears to be severely disturbed, since the focus of the MO was fully transferred to the activity with the SLS to reach a desirable result with the LA. This effect is a subjective interpretation of the researcher, and was not quantified during the data analysis. But it was apparent that the LP of the LA tries to exert extra force on the SLS the reposition the luminaire, after which the LP switch over to a two-handed LAs; or when the SLS pendant system were fully locked, in which moving it by using the sterile handle was completely impossible, the circulating nurse helped to complete the LA. Besides these severe events, a total of 202 LAs were noted as a non-smooth movement. During 1 of those the LP could not initiate a system motion, lacking the required force. A second (stronger) LP took over to produce the desired directionality adjustment.

There are other insights from the observation study that hint at mechanical difficulties during the SLS and LP interaction: In 162 of the 364 LAs the trajectory did not occur along the shortest path length in 3D. It is reasonable that this is due the assumed force distribution as stated in Figure 35, whereby the LP 'chooses' a repositioning of the luminaire along the path of least resistance. These manipulation issues can occur when there is a translational luminaire reposition, especially when there is a risk that the pendant arms reach a near parallel or serial configuration during the repositioning of the luminaire.

To define the luminaire location luminaire during the LA, moment arm (L) of Eq. 1 - was estimated based on the video images and the SLS work field luminaire was divided into three regions (Fig. 36):

1. *Central work field*: In this region the luminaire is suspended directly below the central joint, where the SLS is connected to the ceiling suspension. In this field the system pendant arms are (almost) in parallel configuration and L is at max 47.5 cm., equal to the radius of the luminaire;
2. *Mid work field*: The luminaire is in the region between the central and peripheral field, and the angle between the pendant arm is in a range of: $47.5 \leq L \leq 187$ cm.;
3. *Peripheral work field*: The luminaire is in the peripheral region. The pendant arms are (almost) in serial configuration, and L is $187 \leq L \leq 190$[4] cm.

Figure 36 - Top view of SLS work field regions in OR setting.

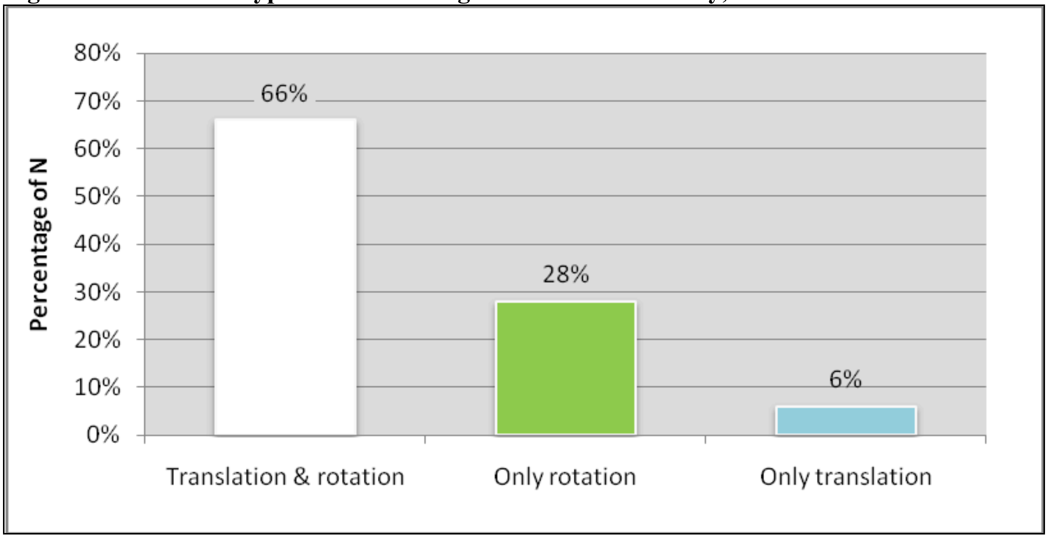


The top view of an operation room (OR) setting shows the luminaire above the OR table. The working range of the OR luminaire in the total work field is divided into three circular regions, in which the luminaire can be located during a LA. The boundary of the work field regions are formatted as the dashed black colour line.

[4] Data based on self made measurement. Berchtold technical indicates a max. swivel radius of 193 cm. [5, page 32)

The risk of a mechanical difficulty during a LA is rather high, considering the previous defined work field regions. The recorded video images showed that 72 % of the 249 LA involved a translational repositioning of the luminaire. Almost 30% were pure rotations of the luminaire, consisting of adjustments of the luminaire to relocate the light pattern on the wound (Fig. 37). Since only 47 of the 249 LAs entirely took place in the mid work field, 81 % of the 249 LAs entailed a repositioning of the luminaire in which there was a possibility of parallel or serial pendant arms alignment (Table 9).

Figure 37 - Different types of LAs during the observation study, N = 249.



The occurrence of different types of LAs during the observation study shows three types of luminaire repositioning: via only translation; only rotation; or a combination of both types.

Table 9 - The work field regions* in which the luminaire was located at start and end of the LA, N =249.

Begin location luminaire	*End location luminaire*	*Number of LAs*
Central work field	Central work field	156
Central work field	Mid work field	22
Central work field	Peripheral work field	0
Mid work field	Central work field	20
Mid work field	Mid work field	51#
Mid work field	Peripheral work field	0
Peripheral work field	Central work field	0
Peripheral work field	Mid work field	0
Peripheral work field	Peripheral work field	0

*** See the page 58 for defined characteristics of the region.**
 # In 4 of the 51 LA the trajectory of the luminaire repositioning from mid work field to mid work field the luminaire passed through the peripheral work field.

Other noteworthy difficulties with the user system interaction during the observation were the following:

- 17 events of collisions of the luminaire against any object: When moving the luminaire around, it bumps into other lights, against the heads of OR-staff (Fig. 38), against its own ceiling mount, and against IV-poles.
- Out of reach SLS: In 4 events the surgeon had to stand up from a sitting posture to reach the luminaire handle and perform the LA

As with the earlier mentioned 24 events of significant mechanical difficulties with the SLS, the concentration of the MO appears to be severely disturbed during these noteworthy difficulties. Again, this effect was not quantified during the study; it is a subjective interpretation of the researcher.

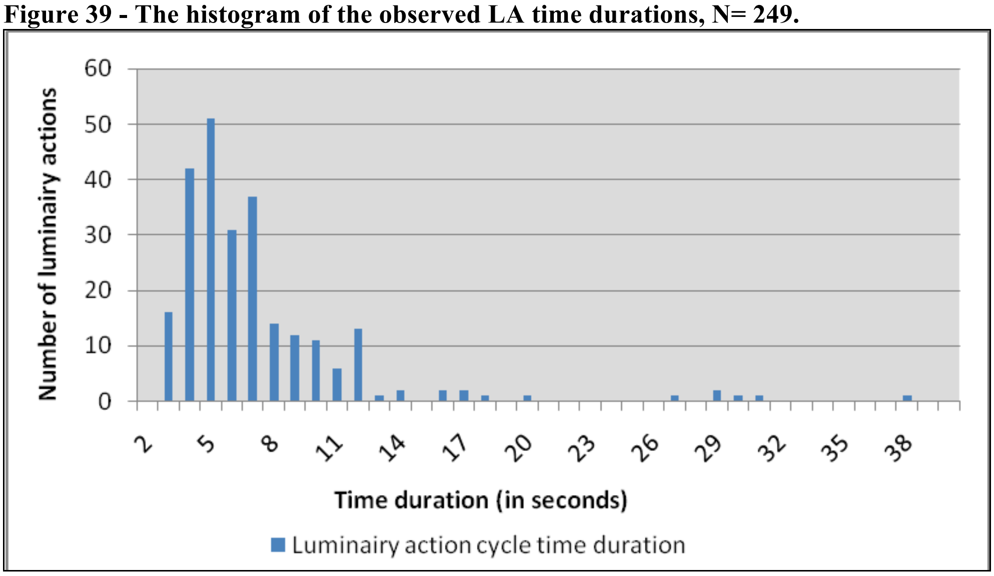
Figure 38 - Observed collision SLS & human.

The still video image displays the start of the collision between the table assistant and the luminaire during an observed LA performed by the surgeon.

Time effects of difficulties during the LA on the SLS

The 249 LAs portrayed a positively distribution (Fig. 39). Most LAs (78%) took less than 8 seconds to complete the action. There are 42 LAs in the range of 4 seconds, 51 LAs in the range of 5 seconds, 31 LAs in the range of 6 seconds and 37 LAs in the range of 7 seconds. The remaining 22% LAs took longer to complete because of difficulties during the LA. The longest LA had the time duration of 37.8 seconds, in which the anaesthetic pole formed an unsolvable obstruction in the desired trajectory of the LA. As a consequence, the performer bungled with the OR luminaire to correct trajectory and finally two performers were necessary to reposition the OR luminaire. The shortest LA cycle was only 2.2 seconds with a pure action time duration of 0.9 seconds. The action was made by the assistant surgeon to perform a small re-adjustment of the OR luminaire.

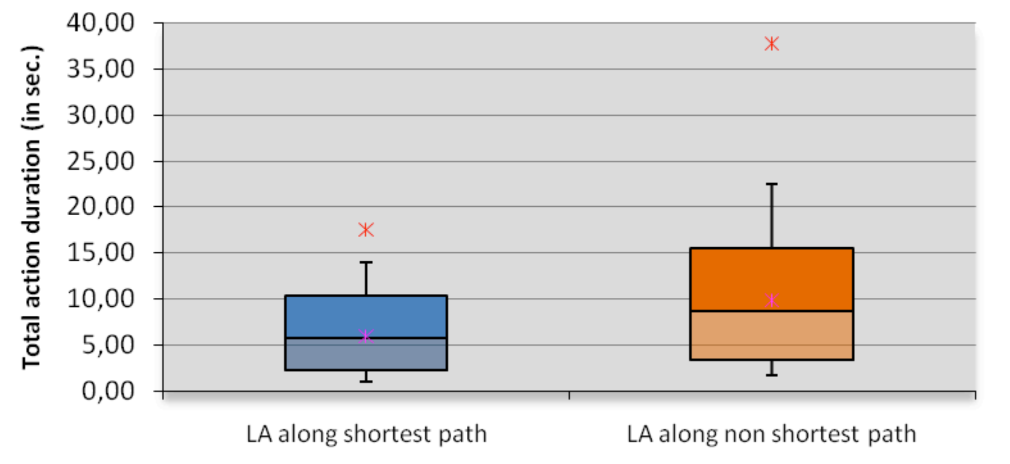
Figure 39 - The histogram of the observed LA time durations, N= 249.



The histogram of the LA time durations (seconds) in the data sample. Most LAs (78%) took less than 8 seconds to complete the action.

An altered LA time duration was perceived when the LAs were divided in sub-datasets by visible ease of control. The LAs along the shortest path in 3D had a decreased average action time duration during the repositioning of the luminaire (stages D-E-F in Fig. 33, page 56) compared to the average LA time duration. Based on the sub-dataset of N = 249 a LA along the shortest path in 3D took 4.5 seconds (N = 139) in contrast with the 6.9 seconds of a LA along the non-shortest path in the 3 D route of the luminaire (N = 110), (Fig. 40).

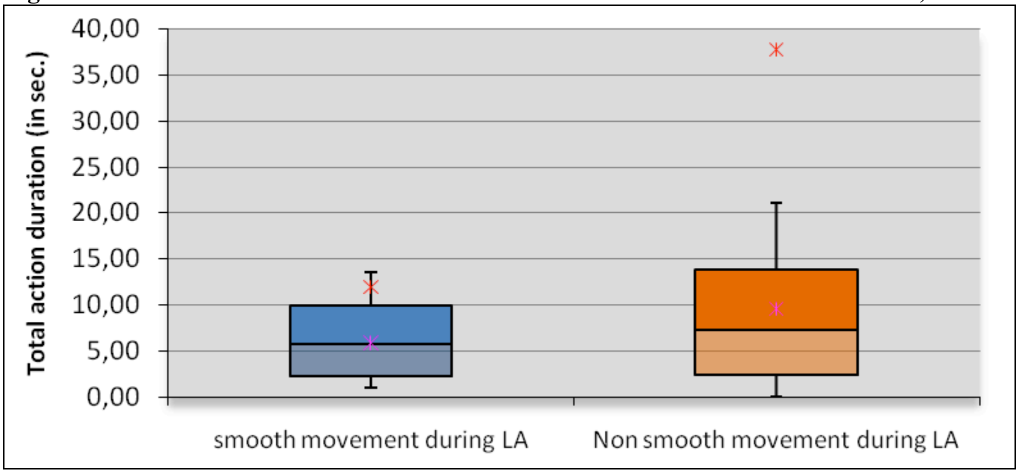
Figure 40 - Correlations between action time duration and path length of LA, N = 249.



The correlation between action time duration and path length of luminairy action (LA) shows that the he average time duration of the action cycle increases with the path length. In the data sample of N = 249 LAs, the blue colour bar contain 139 LAs and the brown colour contains 110 LAs.

Also a difference was perceived if the smoothness of the LA was used to divide the LA dataset of N = 249 LAs. A non-smooth LA movement has a median time duration of 6.3 seconds (N = 105), while a smooth movement LA has a median time duration of 4.2 seconds (N = 144), (Fig. 41).

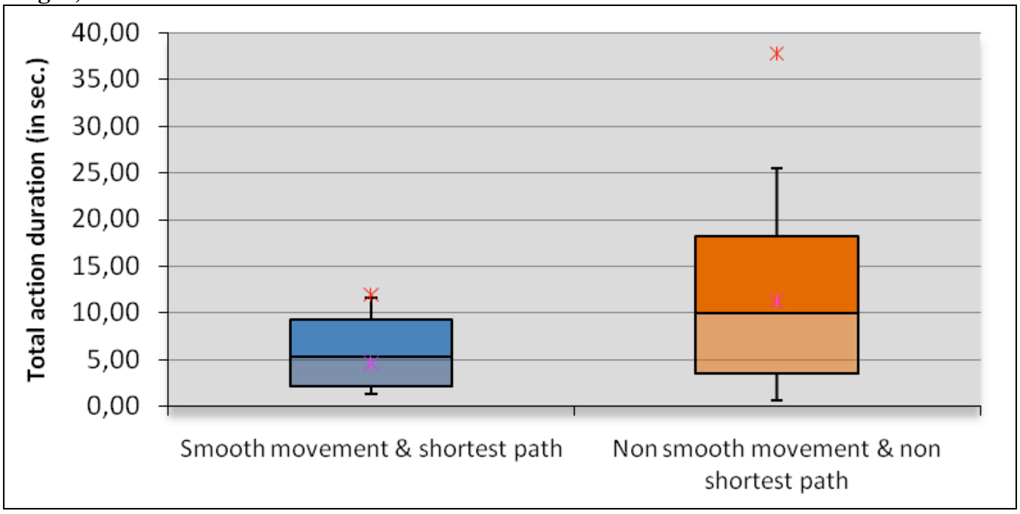
Figure 41 - Correlations between action time duration and smoothness of the LA, N = 249.



The correlations between action time duration and smoothness of the luminairy action (LA) shows that the action time duration increases when the movement is less smooth. In the data sample of N = 249 LAs, the blue colour fill contains 105 LAs and the brown colour fill has 144 LAs.

The time duration is doubled if the both visible ease component of smoothness and path length were taken into account. The time dissimilarity between a smooth shortest path LA (N = 68) and its opposite non smooth non shortest path LA was 4.4 seconds (N = 74), (Fig. 42), which was the largest noted time difference in the LA sub-datasets.

Figure 42 - Correlation between action time duration and both the LA smoothness and path length, N =249.



The correlation between LA time duration and the non-smooth adjustment & non-shortest path length versus the smooth adjustment along the shortest path length shows that the action time duration decreases in the latter case. In the data sample of N = 249 LAs, the blue colour fill has 68 LAs and the brown colour fill has 74 LAs.

4.5 Conclusions of the perioperative observation

During the observation study the user SLS interaction was illustrated, that confirmed the OR light problem and pinpointed the scope of the predicament. It was regarded that the data sample gives a representation of the user system interaction during surgical procedures of open surgery. During the observed 45 hours and 8 minutes of surgery, in total 364 LAs were noticed, resulting in an average period of one LA every 7.4 minutes. The interaction between the medical staff member and the SLS was purely a repositioning of the luminaire, since only one of the three interaction variables was noticed in the observation study. The light beam's focus and the illumination levels were never adapted during the observation period. In addition, most of the LAs took place in the complex stage of the surgical operation while the principal staff member responsible for the successful outcome of the surgical procedure is also the primary LP of the LA.

Observed difficulties were collision of the luminaire against any object, or that the luminaire was hard to reach or control when the surgeon was in a sitting posture. But the primary difficulty appears due to the mechanical construction of the SLS, which primarily manifest itself during the repositioning of the luminaire 2Dimensionalplane of the pendant arms. It was observed that the LP sometimes could not reposition the luminaire; that the luminaire relocations did not take place along the shortest route in 3D space; or that the performer had to apply full force or undertake an oscillating action to start the movement. This might indicate the required force to perform a luminaire reposition has a widespread spectrum. The difficulties resulted into longer time duration of the observed LAs in comparison to the LAs without problems or distracted the medical staff members from the operational activities of the surgical procedure. It appeared that the SLS loses a degree-of-freedom during some of the observed interactions, when the pendant arms are in configuration of parallel or serial alignment. This situation was therefore labelled as a gimbal lock of the SLS and would imply that the severity of the observed problem is related to the location of the SLS luminaire, in relation to the SLS central suspension point.

It was hypothesized that the required force for a LA is dependent of the luminaire location in the work field, due to the fact that the alignment of the SLS pendant arms affects the required force for a LA. In addition, it was beneficial to obtain an impression of the range of the required force for a LA. The next research step is therefore focused on (1) a confirmation of this observation conclusion and to gain insight into the required force to reposition the luminaire and (2) to develop a protocol to test different SLSs on their mechanical characteristics. This was done by constructing a simulation model that allows experimenting with the SLS.

The quintessence of improving SLS is minimizing the need for repositioning the luminaire by the surgical team and minimizing the forces required for these actions. In that way, surgeons will be able to concentrate on their main task, and perform surgery in a well-illuminated wound by a more user-friendly SLS.

5. Method to construct a SLS simulation model

5.1 Introduction

This chapter illustrates the construction of a simulation model of the SLS to evaluate the kinetics of the luminaire repositioning in the SLS work field. Paragraph 5.2 states the goal of the simulation model, followed by Paragraph 5.3 that presents the simulation model instrument in three stages of (1) model outline (2) data collection & implementation of the body part mechanics and SLS resistance behaviour at the interconnecting joints (3) model verification to reach a valid simulation model. Paragraph 5.4 focuses on the data output and analysis, whereas Paragraph 5.5 states the validity, verification and reliability of the simulation model method. The conclusion is presented in the last Paragraph 5.6.

5.2. Goal of the simulation model experiment

The goal of the simulation model was twofold and aimed to clarify the insights of the observation study (cf. chapter 4). The first part of the goal was to investigate the required force for a LA at various locations of luminaire in the work field. It was hypothesized, based on the insights from the observation, that the required force for a LA is dependent of the luminaire location, due to the fact that the alignment of the SLSs pendant arms affects the required force exerted by the LP for a LA on the SLS.

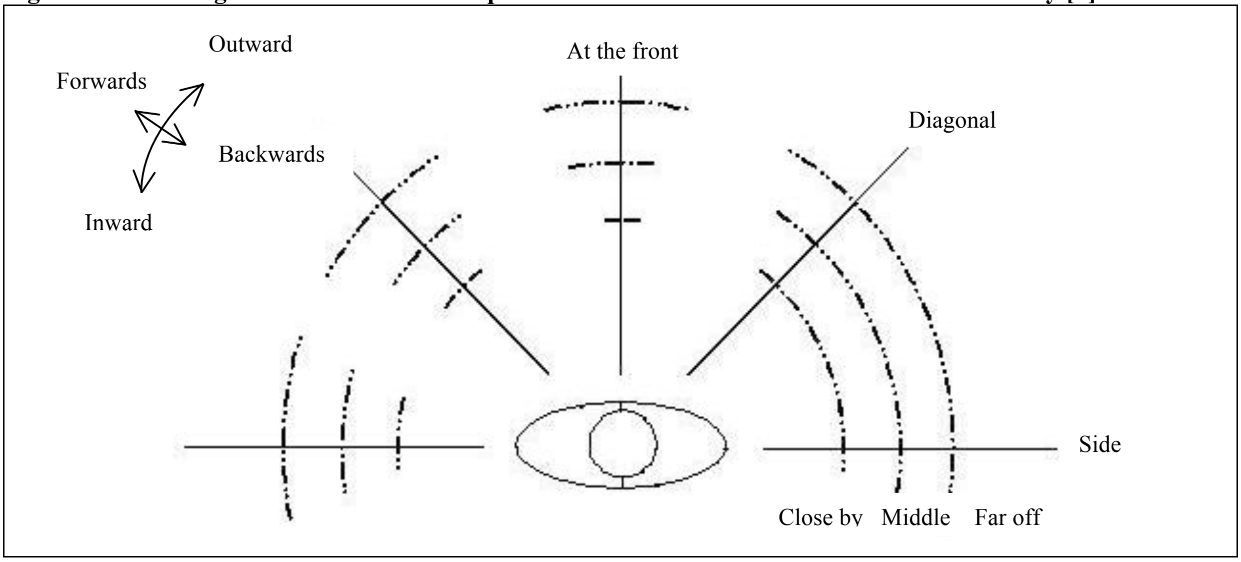
In addition, it was deemed beneficial to obtain insight in the range of the required force for a LA. From an ergonomic point of view, the acceptable forces a human should exert on external bodies with his upper extremities depends on the force direction and the location of the interaction between human and the body in relation to one own position (Fig. 43) [7]. A LA performed at head heights and close proximity of the LP should be in the range of 28 till 62 Newton for forwards and backwards motions, or 11 or 13 Newton for inwards or outwards motion (Table 10).

The second part of the goal was to obtain a valid procedure to test different SLSs on their mechanical characteristics. The outcome of the simulation model is visualized in the next chapter by a generated map of required forces at various OR luminaire locations for luminaire repositioning.

Table 10 - Ergonomic acceptable hand & arm force output (Newton) for human exerted at head height, see also Figure 24 [7]

Direction	*Distance from body*								
		At the front			*Diagonal*			*Side*	
	Close by	*Middle*	*Far off*	*Close by*	*Middle*	*Far off*	*Close by*	*Middle*	*Far off*
Inwards	13	11	9	12	11	8	11	9	7
Outwards	13	12	8	14	13	10	11	9	8
Forwards	28	21	9	25	20	9	28	22	9
Backwards	54	33	15	58	31	16	62	29	14

Figure 43 - 2D Diagram of locations for in plane interaction between human & external body [7].



5.2.1 Explanation and justification of software simulation as the experiment

The simulation mode was basically an 'an ex ante evaluation' of the SLS in order to reach a valid and better design in the future. The simulation model has a twofold objective by constructing a practical experiment that is both economically and socially efficient at this early stage of exploration research.

Simulation modelling favours the traditional "build and test" design methods from an economic viewpoint. Software simulation allows the designing, testing and construction of products at relatively low costs and time. Although physical prototyping is desirable in the future, it is too expensive and time consuming at this stage.

From a practical and social point of view experimenting in the medical environment with a physical prototype is highly undesirable before thorough simulation because of the involved risks and the strain on the medical staff. Virtual prototyping can be used especially in the conceptual design stage in order to significantly reduce the amount of physical testing that is required [15]. The construction of the physical prototype of the SLS is recommended for future research.

5.3 Software simulation instrument

In the simulation model the SLS mechanics were analysed by the application of multibody dynamics[5]. The SLS was then perceived as a multibody system with six individual body parts interconnected by five 1 degree-of-freedom (DOF) joints (Fig. 44). The individual joints and body segments were labelled with a number and simple quotation (Table 11). The SLS mechanics is then defined by the mechanics of the individual parts and resistance behaviour of the system at the interconnecting joints.

The construction of the simulation model is presented in three stages:
1. Set up of the SLS simulation model (cf. 5.3.1);
    a. Description of the (four) model assumptions to simplify the physical system;
    b. Selection of the engineering software to simulate the model;
2. Construct mechanics of the SLS simulation model (cf. 5.3.2);
    Element 1: Construct mechanics of the six individual body parts;
    a. Data collection;
    b. Implementation of the data;
    Element 2: Create resistance behaviour at the five interconnecting joint;
    c. Data collection;
    d. Processing and implementation of the data;
3. Verification of reliability and validity of the simulation model (cf. 5.3.3).

Figure 44 - Technical drawing SLS of Berchtold C series.

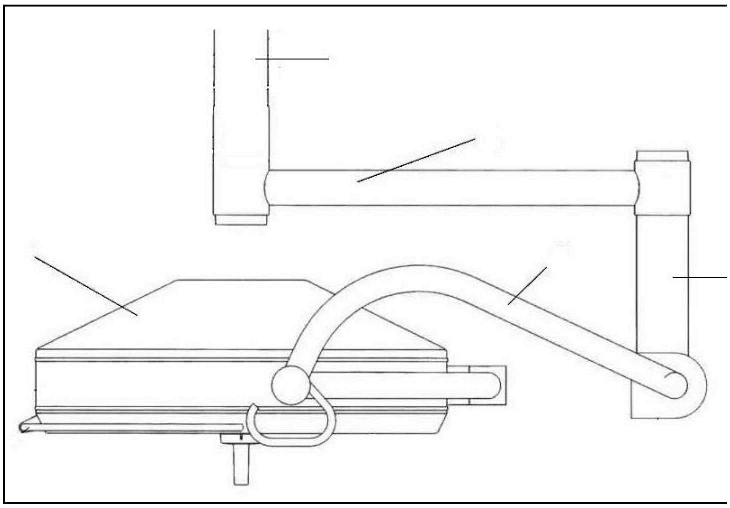
B

3

C

1. Flange tube
2. Horizontal swivel arm.
3. Vertical tube.
4. Hydraulic arm.
5. Horizontal arm.
6. Luminaire.

A. Horizontal swivel arm joint
B. Vertical tube joint
C. Hydraulic arm joint
D. Horizontal arm joint
E. Luminaire joint



technical drawing displays the side view of a surgical lighting
em of brand 'Berchtold', and type 'C series'[3]

Table 11 - Quotation and number, and segment topology at each interconnecting SLS joint.

Joint nr.	*Label*	*Joint interconnect the rigid body segments*
1	Horizontal swivel arm joint	Flange tube & horizontal swivel arm
2	Vertical tube joint	Horizontal swivel arm & vertical tube
3	Hydraulic arm joint	Vertical tube & hydraulic arm
4	Horizontal arm joint	Hydraulic arm & horizontal arm
5	Luminaire joint	Horizontal arm & luminaire

[5] Rigid body dynamics is the study of multibody system motion. It is used frequently in the modelling of physical systems where rotational motion is important, but material deformation has limited effect on the system motion.

5.3.1 Set up of the SLS simulation model

In this first of three stages of the construction of the simulation instrument the set up of the SLS model is defined by the model assumptions and the selection of the simulation software.

5.3.1a Model assumptions

Four assumptions were selected with the intention of approaching reality as much as possible:
1. SLS is a rigid multibody system;
2. SLS rigid body parts are slender rods segments;
3. No margin error is present in the 1 DOF joints;
4. Joint friction behaviour abides the Coulomb's law of friction.

Model assumption 1 of 4: The SLS is a rigid multibody system.
By approximating the SLS as a rigid multibody system the elastic deformation was neglected when describing the mechanical behaviour of the individual part segments. Since the SLS is built out of metal, this assumption is very probable in the simulation time span of seconds[6]. Most likely metal stiffness deformation does not occur during the complete machine life cycle[7]. The dynamical behaviour of individual rigid body parts is described by its inertia properties based on mass and geometry[8].

Model assumption 2 of 4: The individual rigid body segments are slender rods
Besides being rigid, the individual segments of each part were modelled as slender rods. This assumption simplifies the calculation of the mass moment of inertia (Equation 2) and the SLS geometry and structure (cf. 5.3.2b and Fig. 46).

Equation 2 - The formula to calculate the mass moment of inertia of a slender rod

$$\text{Mass moment of inertia} = \frac{(\text{mass of the rigid body}) * (\text{length of the rigid body})^2}{12}$$

Model assumption 3 of 4: There is no margin error in the 1 degree-of-freedom joint.
The third assumption was that interconnected 1DOF joints have no margin error. Joints with margin error contain flexibility that can result into time delay or deviations from the in plane motion trajectory. That behaviour is a challenging and complex modelling problem by itself. There was no reason to presume this model assumption was not correct, since there was no indication of sloppy joints during the friction behaviour measurements (c.f. 5.3.2d).

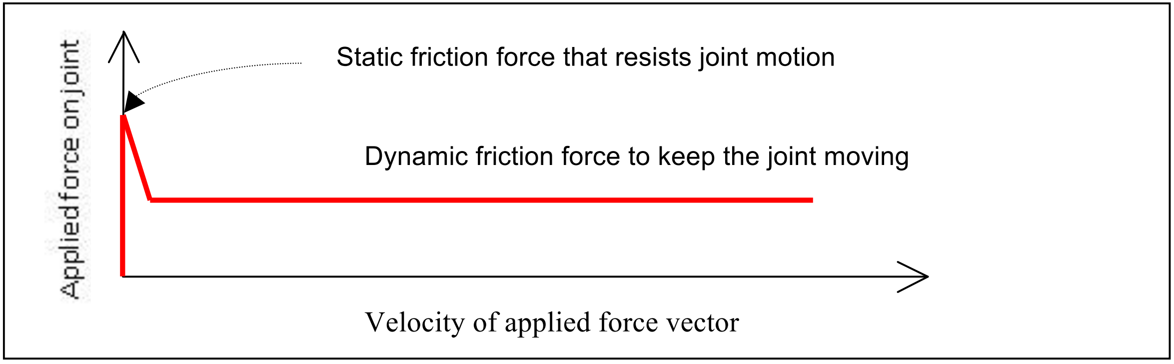
Model assumption 4 of 4: Joint friction behaviour is approximated with Coulomb's law of friction
Friction occurs in all mechanical systems. From the universal laws of friction with known friction phenomena the Coulomb's law of friction was applied in this simulation model to approximate the friction behaviour of the SLS joints. It is an empirically simple approximation and was presumed sufficient as a first approximation of the joint friction behaviour.

[6] In chapter 5 stated that the overall median LA time duration was 5.4 seconds
[7] The forces during the user system interaction throughout the machine life cycle are not expected to have an effect large enough to take into consideration during the model simulation runs.
[8] The mass moment of inertia (kg·m²) is a measure of an object's resistance to changes to its rotation.

In Coulomb's law of friction states that kinetic friction is independent of the sliding velocity. Two characteristics are then needed to define the friction behaviour (Fig. 45):

1. The *static friction* force, which is the critical tangential force (in the plane of the 1DOF joint) that will cause the joint surfaces to start to slide and initiate joint motion.
2. The *dynamic friction* force, which is the tangential force to steady sliding (joint rotational motion) after the joint surfaces start to slip.

Figure 45 - The assumed friction behaviour of the SLS joint



The friction behaviour of the joint according to Coulomb's law of friction: After the applied reaches the value of static friction force, joint motion initiates and the resistance will drop to its dynamic value that is independent of the sliding velocity.

5.3.1b Simulation software

This research used the MSC Adams version 2005 r2 as the software simulation tool. The software had a good fit for the simulation requirements and assumptions in this research. One can define the variables, constraints, and design objectives of the MSC Adams model. When running the model simulation, the software checks the model and automatically formulates and solves the equations of motion for kinematic (static, quasi-static, or dynamic) simulations. As a result, it enables the researcher to create and test the mechanical behaviour of the SLS simulation model both visually and mathematically.

5.3.2 Construct mechanics of the SLS simulation model

The second of the three stages of the simulation model construction was the collection of the mechanical data as input for the SLS simulation model. With the aim of increasing the validity and reliability of the model, the manufacturer and distributor of the Berchtold SLS were approached to provide the technical information of a high detailed level to give insight in both static and dynamic behaviour of the SLS, such as technical drawings of individual segment geometry, joint friction data and mass distribution. Unfortunately, the data obtained from the distributor only contained global SLS technical information:

- Total mass of the SLS is 121 kg., and the luminaire maximal swivel radius is 190[9] cm, and;
- All joint friction mechanisms are passive. The friction behaviour of the joint interconnecting the vertical tube and the hydraulic arm is caused by a hydraulic technique whereas the other joints are plate friction joints.

In addition, based on the intention of ‘to measure is to know’ measurements were performed on the SLS to (1) complement and double check the technical data obtained from Berchtold distributor as input for the model construction; and (2) to acquire independent data for the validation of the SLS model. The sparse technical information provided by the SLS distributor made it necessary to define an extra assumption concerning the mass distribution; and to assemble all detailed system mechanics by manual measurements and perform a sensitivity analysis on the simulation parameters concerning the necessary approximations.

All measurements were performed on a Berchtold SLS C series situated at the Reinier de Graaf Gasthuis hospital in Delft, which is the same SLS from the observation study. The data collection and implementation steps are described below in two phases:

- Phase 1 Mechanics of the six individual body parts;
- Phase 2 Resistance behaviour of each interconnecting joint;

5.3.2a Phase 1 Mechanics of the six individual body parts: data collection

The mechanics of the individual rigid body segments are modelled by two parameters of (1) the geometry of the individual segments and the (2) mass (distribution) of individual segments. With this input the MSC Adams is able to calculate the moment of inertia of each body part and its segments. The mass distribution over the SLS was based on a volume ratio; each part body was given a fraction of the total mass in the same ratio as the body part volume in relation to the total SLS volume, and the geometry data was obtained using a tape measure on the SLS (Appendix C).

The luminaire then obtains the largest mass in the SLS. It is reasonable to assume that the luminaire has the greatest mass, as it is the largest body part. The mass distribution does not affect the inertia of the SLS as a total, but affect the inertia of the individual body parts. Besides, the model simulation runs were performed at low constant velocities wherein mass inertia effects are nonexistent. Since it was impossible to check the actual mass distribution, this approximation was taken into account during a model sensitivity analysis.

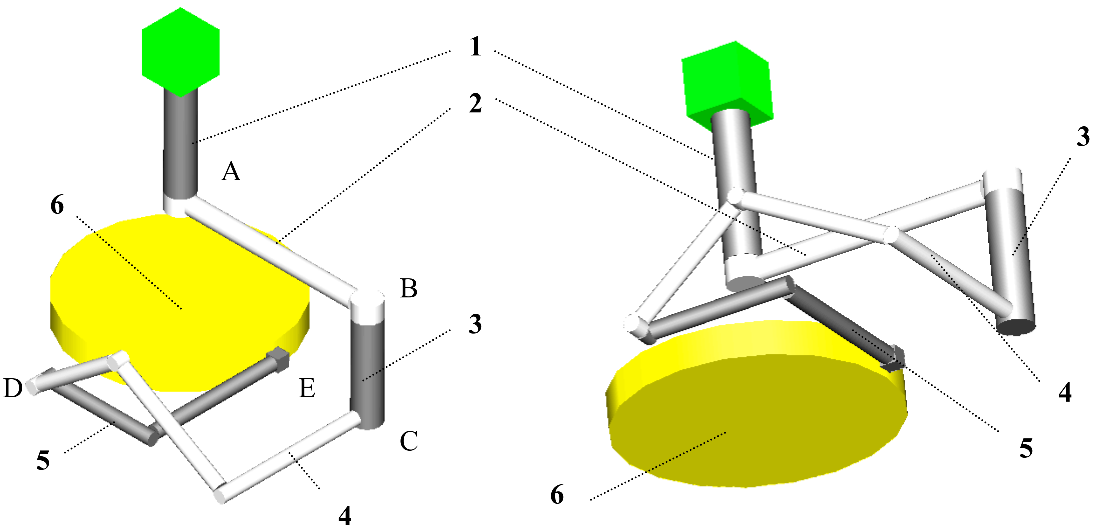
[9] Data based on self made measurements (see Appendix C). The Berchtold technical indicates a max. swivel radius of 193 cm.[4, page 32]

5.3.2b Aspect 1 Mechanics of the six individual body parts: data implementation

The geometry and mass information of the body parts were processed into MSC Adams software environment, in which the part segments were modelled as MSC Adams rigid body parts. The five interconnection joints were modelled as revolute joints that function as constraints between the parts to restrain the models degree-of-freedom to complete the outline of the model outline (Fig. 46. Appendix F provides the full model topology).

As can been seen the SLS geometry and structure were simplified during this modelling process step: the round curves of the segment arms were simulated with rectangular spatial features. This simplification is most visible in the luminaire and the hydraulic arm geometry. Although the researcher needed to take this simplification into consideration, it was assumed that it has a minimal effect on the mechanics of the model. The validation of the simplified model will be checked in stage four of the model instrument presentation.

Figure 46 - The SLS model outline from two viewpoints



The MSC Adams model of the SLS with the six rigid body parts: (1) flange tube; (2) horizontal swivel arm; (3) vertical tube; (4) hydraulic arm; (5) horizontal arm, and; (6) luminaire. The element in green acts a ground part and functions in MSC Adams as a base part on which the model was connected. (A) horizontal swivel arm joint (B) vertical tube joint (C) hydraulic arm joint (D) horizontal arm joint (E) luminaire joint.

5.3.2c Phase 2 Resistance behaviour at each interconnecting joints: data collection

The resistance behaviour of the SLS consists of the joint friction behaviour with possible some effects of the weight of the SLS body parts, and the mass moment of inertia of the segment parts. The data collection of the resistance behaviour at the interconnecting joints is more complex than the previous modelling phase of the mechanics of the body parts. Therefore the SLS resistance data collection is presented in five steps: Measurement material; - protocol; - interpretation; and the measurement output.

Measurement material
The measurement material consisted of a force sensor (type ZFA loadcell 100kg) connected to an amplifier (type HBM DA 3418). The signal from the force sensor was stored via an AC data converter (NI-USB-6008: 12-Bit, 10 kS/s) on a PC, with Microsoft Windows XP operating software using NI (National Instruments) Labview version 8.2. NI Labview produces an output as in the form of Microsoft Windows notepad files which were loaded into Microsoft Office 2007 Excel and Matlab version 2007 for data analysis and visual presentation. The calibration of the force sensor is given in Appendix D.

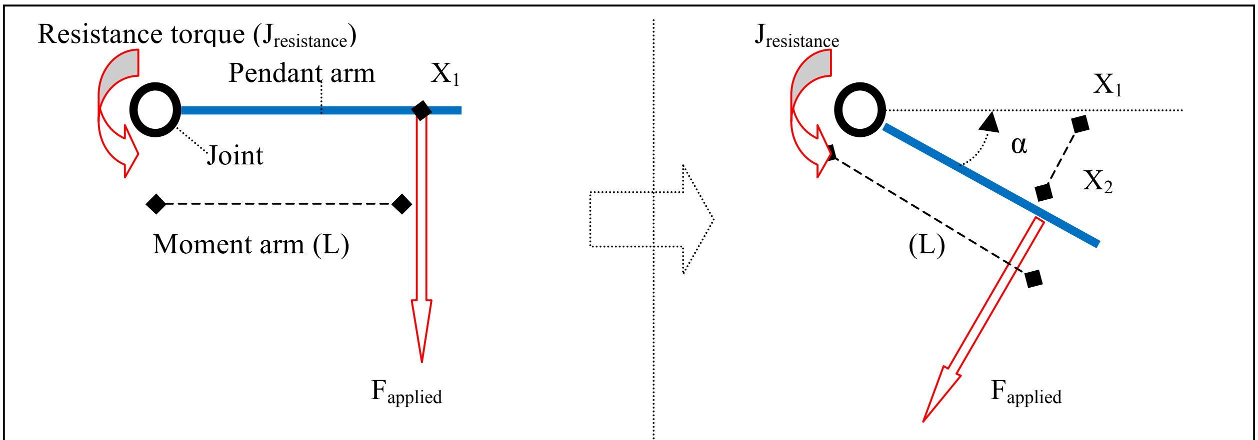
An angular velocity sensor (gyro sensor) was omitted in the measurement material due to economical and operational reasons. After contact with electronic manufacturers, it became apparent that the suitable sensor types are too expensive. And the method of sensor operation is very susceptible to the application of the device on the SLS body segments to obtain a relevant signal, and required a mounting that could not guarantee temporary attachment on the SLS. That was deemed unfeasible.

Measurement protocol
The SLS resistance behaviour was measured at each individual joint according to the following protocol:

- The force sensor was attached on one side on the SLS body part using a tie rape, the other side was manually held and controlled by the researcher;
- A force ($F_{applied}$) was applied manually at moment arm (L) perpendicular on the body part to create a torque ($F_{applied}$*L) around the individual joint degrees in the plane of the 1DOF joint (Fig. 47). The SLS resistance behaviour to oppose joint motion at each was expressed as a torque ($J_{resistance}$);
- During each individual measurement the joint was rotated an equal angle in a time span of 4.5 sec. while considering the identified protocol conditions for a reliable measurement (Fig. 48);
    - A laser pen was attached to each pendant arm to track the crossed distance (X_1-X_2);
    - The force was continuously recorded with the previously depicted materials;
    - Measurement time was recorded via NI Labview;
    - The joint motion was visually observed while tracking the applied force trajectory. At the threshold of motion, the time and force were noted. The time duration and force magnitude of both static and dynamic region was tracked with the visual inspection applicable in NI Labview, which presents a continuous real time image of the measurement data, while recording time and the input from the force sensor data.

The consequential average angular velocities of each joint measurement were in the range of 5 till 12 degrees per second (Table 12). The different angular velocities of each joint were the result of the fact that the traversed angle during joint rotation was different between each SLS joint while the measurement time span did not vary.

Figure 47 - 2D top view of initial (left side) & end configuration (right side) of joint resistance measurement



The resistance torque ($J_{resistance}$) measurement is performed by manual applying a force, creating an applied moment ($F_{applied}$*L) on the joint to induce motion. This measurement was performed at each individual joint.

Figure 48 - The identified protocol conditions for a reliable joint resistance measurement

- To reduce possible errors during the measurement process, pilots were executed in advance.
- An identical initial system configuration for each measurement, to gain a consistent data sample that can be processed in total. The initial configuration of Figure 40 and 49 was used in the measurements;
- The force application was aimed to produce a constant low velocity of each pendant arm, to annul the mass moment of inertia;
- Force application must be at a perpendicular angle on the SLS body part in the plane of 1DOF joint to reduce observational error:
  - The angle between the force sensor and pendant arm was checked at start and end of the motion using a digital spirit level of the brand Laserliner;
  - A cross check spirit level, attached on the force sensor with two sided duct tape, was used to visually check the force direction was stable during the motion;
- Rotate each individual joint along an equal angle in an equal time span of 4.5 seconds.

Figure 49 - The initial configuration of the SLS during the friction behaviour measurements.

Table 12 - The moment arm of the applied force (L) and the calculated angular joint velocities of each individual joint based on the tracked X1 - X¬2 (See also Fig. 47), N 18.

Joint nr.	*Moment arm (L)*	*Average angular joint velocity (Degrees/sec)*
1	82	12
2	82	6
3	82	6
4	82	5
5	82	12

Beforehand identified interpretation of the measurement data and necessary approximations

If the measurement protocol was implemented correctly and the Coulomb's law of friction assumption is adequate for SLS joint friction behaviour, the measurement data arrays needed to shows a curve like trajectory, as schematically presented in Figure 50, since:

- In the static region, the applied torque needs to increase at the start of the measurement to reach the value of the static resistance of the individual joint. At the threshold of motion, the applied torque equals the static behaviour of the individual joint;
- After the threshold of motion the resistance behaviour transits from the static into the dynamic region. A nett torque is introduced shortly with a magnitude of (ΔA_1) and a time duration of (ΔT_2) as the kinetic energy to fuel the joint motion;
- When the force is applied at constant velocity, the required applied force to rotate the joint will drop due a lower value as the dynamic friction torque value is lower than the static friction torque value. The nett torque will fade out as the effects of mass moment of inertia and kinetic energy do not play a role in constant motions; And,
- A consistently performed method will produce consistently equal data output.

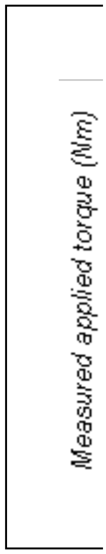
An approximation of the resistance behaviour is mandatory, during which the data sample needed to be examined for possible faults during the protocol implementation. Several risks were identified, due to the simplicity of the protocol method and the limited available technical data from external sources, in which the combination of a manual force application without detailed insight of the force direction vector and real time angular joint velocity is precarious:

- Acceleration in the manually applied force;
    - In the transition from static to dynamic region this could lead to an identified static resistance value that will be too large (ΔSt_1) or a longer time duration from threshold of motion to the peak value in the measured data (ΔT_1) or the total time duration of the transition from threshold of motion to constant dynamic resistance behaviour (ΔT_2); Or
    - In the dynamic region a constant acceleration of the manually applied force the value would have a steadily higher value (ΔDyn_2) than the real dynamic resistance of the SLS; Or
- A visually unnoticed error in the application of the force direction vector; Or
- Non consistent implementation of measurement protocol.

Other risks in the measurement protocol implementation were not considered in detail, since they are easily identified as they would not lead to the required curve like trajectory of the resistance behaviour.

Therefore the consistency of measurement data arrays was assessed visually and statistically with a regression analysis (next Paragraph). As a standard modelling step the validity and reliability of the SLS simulation model was verified (cf. 5.3.3). Finally, a sensitivity analysis of the resistance behaviour on the force output of the model was performed to check that the SLS model was not sensitive to the approximations (cf. 6.3.1).

Figure 50 - Schematic representation of the joint resistance measured data.



A schematic representation to explain the factors in the measurement data: during the force measurement the resulting applied torque on each individual joint will create a joint motion. In the static region the measured data equals the friction torque (red line). In the dynamic region the measured torque consists of the friction (partly dashed red line) and nett torque (green line).

Measurement data output

Eighteen force measurements were performed on each individual joint. The dataset $F_{measurement}$ (N = 18 per joint), was divided into two equal sized sub-datasets and multiplied by its moment arm (L) to obtain the resistance behaviour as torques; T_{model_input} and $T_{validation}$. The average value per joint of T_{model_input} was used for the model approximation of the resistance behaviour; the average of $T_{validation}$ functioned as an independent dataset for the model validation.

- Both a visual inspection and regression analysis of the two datasets illustrated that the measurement was performed consistently and that the assumption of Coulomb's Law of friction is proper :The visualization of the data array illustrated that the measured resistance torques of each individual joint have comparable trajectories, while the manually applied force attained a constant values in the dynamic region (Figures 51 and 52 present plots of the individual data arrays and mean of the measured data of the hydraulic joint. Figure 53 presents the mean of each individual joint measured data arrays, both T_{model_input} and $T_{validation}$. Appendix E shows plots of all data arrays).

- A regression analysis between the two datasets (T_{model_input} and $T_{validation}$) confirmed that two subsets are equivalent. The goodness of fit (R^2-value) between all the five joints is near 1, with a significance of fit (overall p-value), is below 0.05 (Table 8). This also implied that the two subset were beneficial for the model validation, as each set should result in equal model simulation output

It should be noted that the resistance behaviour of joint 1 had a relatively long time duration from the threshold of motion to the constant dynamic (2.4 seconds), combined with the angular velocity presumably indicates an undesirable high acceleration at the start of the joint motion (Table 7).

Table 13 - Regression analysis between the two sub datasets: model input and - validation sub dataset.

Joint nr.	*Joint label*	*Goodness of fit (R^2)*	*Significance of fit (P-value)*	*Standard error*
1	Horizontal swivel arm joint	0,98	2,2E-28	2,0
2	Vertical tube joint	0,97	2,5E-23	1,2
3	Hydraulic arm joint	0,97	2,5E-25	0,7
4	Horizontal arm joint	0,99	1,3E-34	0,1
5	Luminaire joint	0,99	2,4E-35	0,1

Figure 51 - Subset T_{model_input} of the hydraulic joint data arrays in the total measurement dataset.

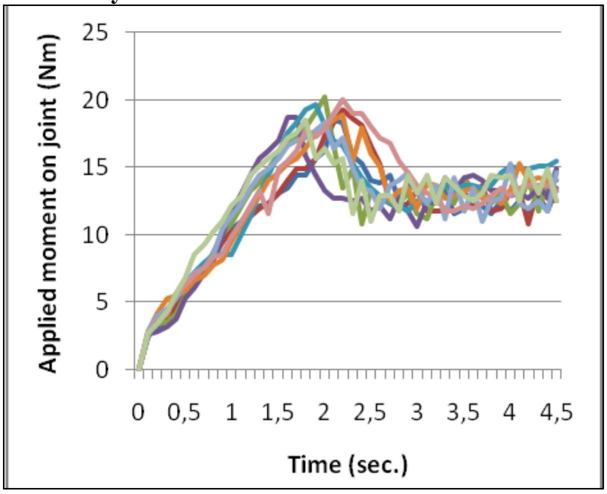


Figure 52 - Mean of subset Tmodel_input of hydraulic joint data arrays in the total measurement dataset.

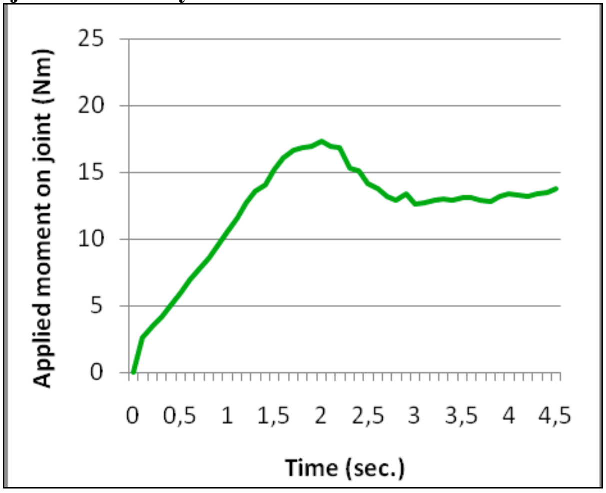
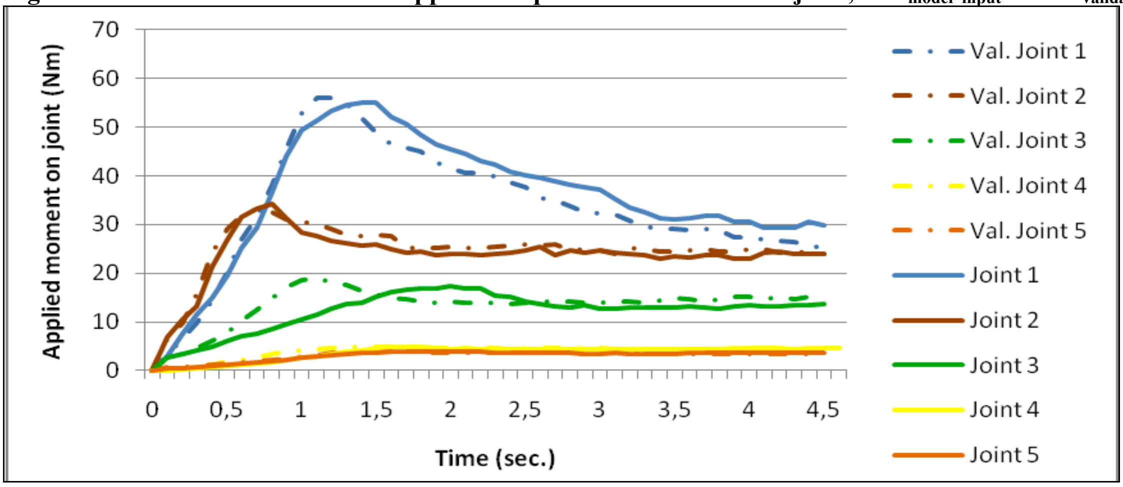


Figure 53 - The mean of measured applied torques at each individual joint, of T_{model_input} and $T_{validation}$



The mean of the applied torque measurements to initiate joint motion in the sub-dataset of model input (N, $T_{model\_input} = 9$,) sub-dataset of model validation (N, $T_{model\_validation} = 9$). Table 11 (page 66) clarifies the labelling of each joint number. T_{model_input} is presented in solid lines, while $T_{model\_validation}$ is presented in dash dot line style. Joint 1 is in the blue colour, joint 2 has a brown coloured line, joint 3a green colour, joint 4 a yellow colour and joint 5 has an orange colour.

5.3.2d Phase 2 Resistance behaviour of each interconnecting joints: data implementation

The model resistance data was approximated at each interconnecting joint via an iteration method, that was assembled in three steps (Fig. 54) using both the fitted data and average value of T_{model_input} after the splitting of the total dataset $F_{measurement}$ (N = 18 per joint):

(1) The average trajectory of T_{model_input} was fitted based on the Coulomb's Law of friction (Table 14): The max value served as the static resistance. As a double check, this value was compared with the force quantity at the threshold of motion, which was noted during the applied force measurement; the force data trajectory in the dynamic region was fitted in Microsoft Excel with a 6th order polynomial trend line. The first derivative of the polynomial provided the start of the relatively constant state of the data array. The value of that steady segment period was used as the dynamic friction value. As to be expected, the fitted parameters of T_{model_input} depict that joint 1 has the highest static and dynamic resistance values as the central joint of the SLS. Subsequently joint 5 has the lowest resistance values as the most peripheral joint in the system connected to the luminaire.

Table 14 - The fitted resistance torque parameters in T_{model_input} for each individual joint, N = 9.

Joint nr.	*Torque at threshold of motion (Nm)*	*Measurement time at threshold of motion (sec)*	*Average dynamic friction (Nm)*	*Measurement time at start average dynamic friction(sec)*	*Angular velocity joint (Degrees/sec)*
1	55.1	1.4	30.8	3.5	12
2	34.2	0.8	23.9	1.6	6
3	17.3	2	13.1	2.7	6
4	4.9	1.6	4.4	2.5	8
5	3.9	1.6	3.5	2.6	12

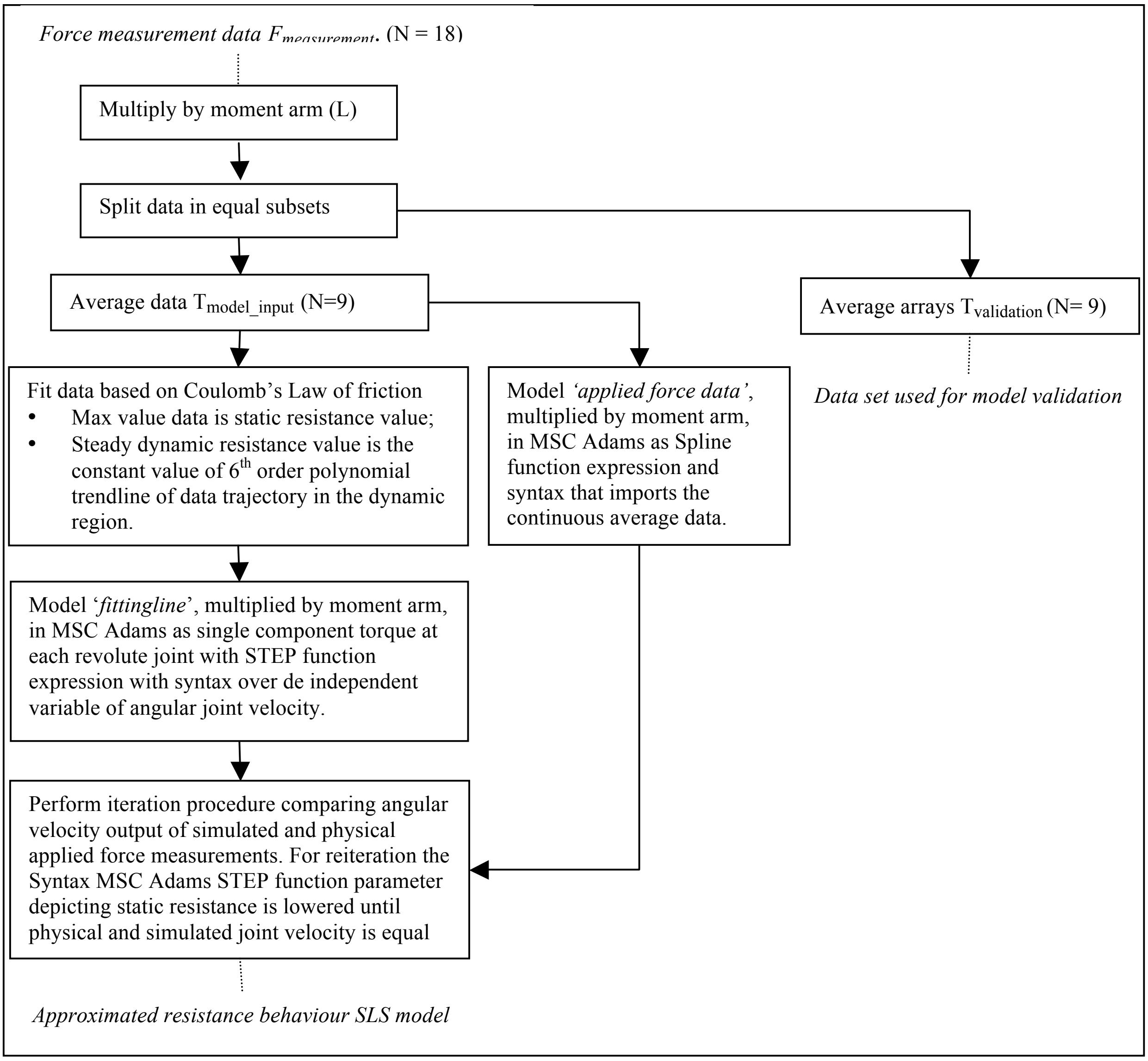
(2) Two counteracting single component torques were modelled in MSC Adams at each revolute joint with different syntaxes. One to simulate the applied torque, the other the resistance behaviour:
   a. The syntax for the modelled resistance torque was the MSC Adams STEP function expression[10], an apt algorithm to depict the behaviour of the Coulomb's law of friction. For the initial iteration step the syntax was based on the fitted parameters of T_{model_input} in which the transition from static to dynamic parameter was dependent on the angular joint velocity of the SLS model;
   b. The syntax for the simulated applied torque was the MSC Adams SPLINE function expression, an apt algorithm to imported the mean of T_{model_input} so that the simulated applied torque has an identical behaviour as the physical applied torque;

(3) Simulation runs were performed for 4.5 seconds while the model was subjected to the simulated applied torque on one joint corresponding with the manually applied torque, multiplied by its moment arm (L). After each run the angular joint velocity of the physical and model SLS were compared. The resistance data was adjusted for the reiteration until physical and simulated joint velocity is equal and the appropriate approximation of the resistance value is attained.

The simulation model is now only appropriate for low constant (angular joint) velocities, where viscous behaviour and mass inertia effects do no play a role in the system dynamics, due to the measurement protocol.

[10] The MSC Adams STEP function is described in appendix G.

Figure 54 - Diagram describing SLS model construction of approximated resistance behaviour.



A relevant aspect occurred in joint 1. To obtain an equal angular joint between the real life and simulated applied force measurement, the assumption of Coulomb's Law of friction was not fully applicable for the approximated friction behaviour. The dynamic resistance behaviour was up to a speed of 11.55 degrees per seconds dependent on the angular joint velocity. It was deemed credible to that is an indication that inertia effects were incorporated during the joint resistance behaviour measurement due to an unnoticed angular acceleration. It is impossible that the joint shows a viscoelastic or viscous friction behaviour since joint 1 is a passive plate joint. The sensitivity of the SLS model on the transition behaviour from static to dynamic resistance on the force output will be evaluated for all joints in the sensitivity analysis (cf. 6.3.1).

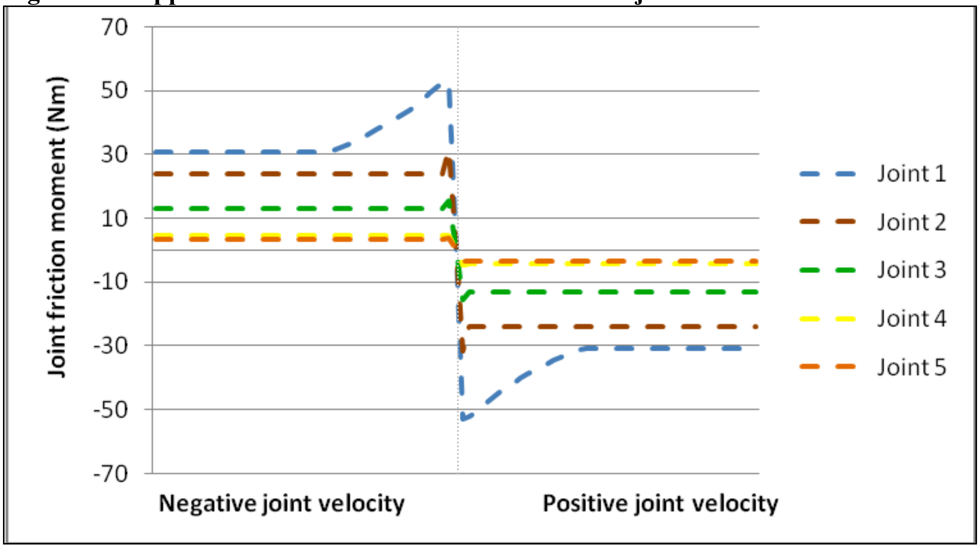
Also, it was necessary to perform the model simulation without force of gravity. The assumed mass distribution did not result into realistic angular velocity of the hydraulic joint. During static configuration, the hydraulic joint buckled under the force of gravity. And during the dynamic simulation the joint would accelerate tremendously, which resulted into increasing angular velocity. The weight of the luminaire influences this behaviour, as the gravity force on this body part results in a moment that the measured resistance torque of the hydraulic joint does not counter. The only option is to neglect the force of gravity, since it was not possible to obtain information of the mass distribution of the Berchtold SLS.

It was deemed that this deficiency had a minimal diminishing value on the force output of the model simulation forces due to multiple reasons. Gravity affects the weight of the SLS. The interesting SLS resistance behaviour is during the repositioning of the luminaire 2D plane of the pendant arms, which perpendicular to the field of gravity. In that plane the resistance to the SLS motions due to gravitational forces is therefore minimal or even none existent. In addition, the measured joint resistance behaviour includes the SLS weight effect - under influence of gravity - during the repositioning of the luminaire. These effects were not omitted during the modelling steps, so it is also present in the simulation model.

Lastly, in order to increase the accuracy of the numerical integration of MSC the integrator command in MSC Adams was altered from GSTIFF to S12_GSTIFF integrator modus. In that way the software can handle small integration time steps more effectively. The mechanical behaviour of the total system was now deemed complete, and ready for the validation and verification step.

Figure 55 shows the definitive approximated resistance behaviour of the MSC Adams simulation model at each individual joint and Table 15 gives the simulated static and dynamic friction torque at each individual joint. Appendix H presents the details of the modelled MSC Adams STEP function expressions of the single component torques.

Figure 55 - Approximated resistance behaviour at each joint based on Coulomb's Law of friction, N = 9.



Trajectory of the approximated Coulomb resistance behaviour simulated in MSC Adams. joint 1 = dashed line blue colour, joint 2 = dashed line brown colour, joint 3 = dashed line green colour, joint 4 = dashed line yellow colour and joint 5 = dashed line orange colour.

Table 15 - Approximated resistance behaviour at each joint based on Coulomb's Law of friction, N = 9.

Joint nr.	*Static torque (Nm)*	*Average dynamic torque (Nm)*	*Angular joint velocity at start dynamic region (degrees/ sec)*
1	53.25	30.8	11.55
2	33.4	23.9	0.03
3	18.4	13.1	0.03
4	4.75	4.4	0.03
5	3.8	3.5	0.03

5.3.3 Verification of reliability and validity of the SLS simulation model.

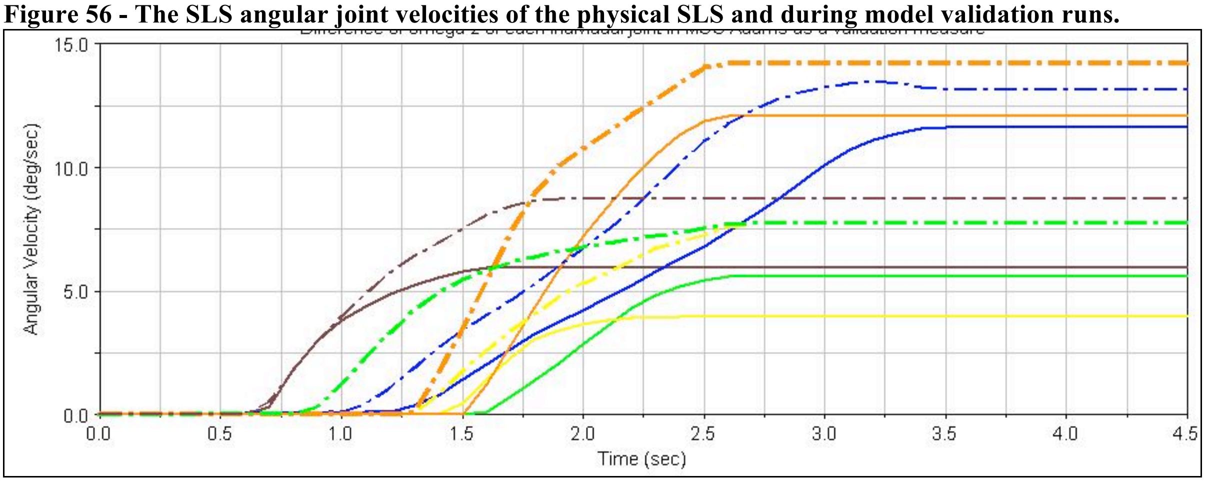
The final of three stages of the simulation model construction was the verification of the simulation model's reliability[11] and validity. As a quick primer, model verification refers to a process aimed at answering the question "did we build the model right?" and model validation refers to a process aimed at answering the question "did we build the right model so that the results are credible?" [14].

Model validation
The validation of the model was confirmed based on the required knowledge perspective 'what force is required to generate system motion' as described below, via two alternative procedures by assessing a mechanical ratio between the physical and model SLS to verify the four utilized model assumptions. Both procedures independently indicated that the simulation model is reasonably valid, as the differences in mechanics between real SLS and the simulation model are in the same order of magnitude.

Model validation procedure 1: at each individual joint
Procedure 1 provided a model validation measure as a velocity ratio at each of the individual interconnecting joints by comparing the tracked angular joint velocities during the force measurement on the physical SLS (c.f. 5.3.2.) and SLS model angular revolute joint velocities after subjection the externally applied mean torque of the independent dataset $T_{validation}$.

This validation procedure indicated that the SLS model is a valid representation of the physical SLS, as the differences between SLS and the simulation model are in the same order of magnitude and the angular joint motions obtained a constant value. The calculated validation ratio was in the range of 1.1 and 1.5, based on the simulated and tracked angular velocities of each individual joint (Figure 56 and Table 16). This indicated that the simulated angular velocities during validation are higher than the tracked angular velocities during the force measurements, especially for the hydraulic resistance torque. An exact cause of difference between simulation model and SLS was unclear, but the validation dataset ($T_{validation}$) has a slightly longer transition in time of the resistance behaviour trajectory from the torque (Nm) at threshold of motion until the average dynamic torque than the sub-dataset $T_{model\_input..}$ This difference results in higher nett torque to fuel the angular joint motions during the simulation runs with a higher angular velocity as a consequence. The performed sensitivity showed that the SLS simulation model output is to a limited extend sensitive for these approximations (cf. 6.3.1).

Figure 56 - The SLS angular joint velocities of the physical SLS and during model validation runs.



A visualisation of the joint velocities at each individual joint of both the tracked angular joint velocities in the sub-dataset T_{model_input} and simulated angular joint velocities based on the sub-datasets T_{model_input}. The simulated angular joint velocities are in the dashed dot line style, while the tracked angular joint velocities are in solid line style. Joint 1 (blue colour) joint 2 (brown colour) joint 3 (green colour) joint 4 (yellow colour) joint 5 (orange colour).

[11] In software engineering the reliability of the model is often called model verification. That jargon will be ignored in this thesis in order to use consistent jargon in both observation and experiment research method.

Table 16 - Model validation measure as a velocity ratio at each individual joint of the model and physical SLS.

Joint nr.	*Angular joint velocity with the input simulation data (Degrees/sec)*	*Angular joint velocity with the validation data (Degrees/sec)*	*Ratio between input and validation data*
1	12	13,1	1,1
2	6	8,7	1,4
3	6	7,8	1,3
4	5	7,7	1,5
5	12	14,2	1,2

The validation measure of the SLS model is calculated at each individual joint, between the tracked angular joint velocities in the sub-dataset $T_{validation}$ and simulated angular joint velocities in the model based on the sub-datasets T_{model_input}.

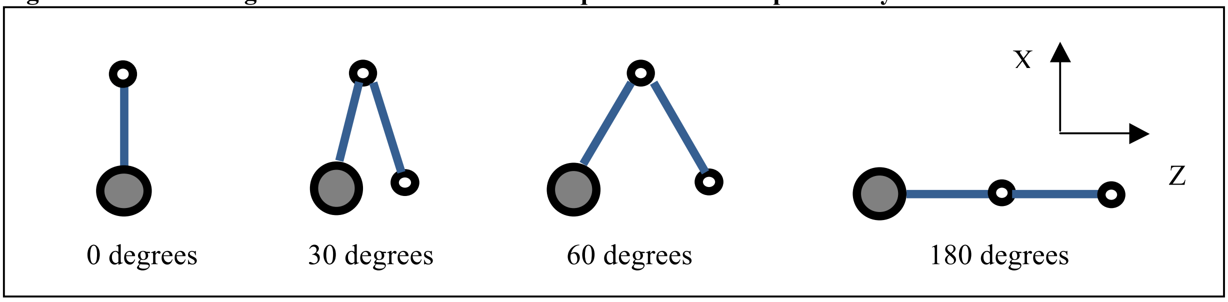
Model validation procedure 2: the system as a total

Validation procedure 2 provided a model validation measure as a force ratio for system as a total by comparing the required forces to initiate a translational luminaire repositioning between the model and real system at four system configurations (Fig. 57) in two force vector directions (x & z).

This validation procedure required as input that additional force measurements on the SLS as a total, which were with measurement protocol similar to the one formulated in Paragraph 5.3.2. These additional force measurements were considered complicated, due to the fact that the luminaire was difficult to control during the these manual measurements. Although the possible reason for this behaviour was not studied, it could indicate that forces are necessary to stabilise the luminaire additional to the forces required to reposition the luminaire in the 2D plane. The measured force at various luminaire positions at the threshold of SLS motion were in the range from 27.5 Newton to plus 100 Newton, in the pendant arm configuration of gimbal lock (Table 17).

This validation procedure indicated that the SLS model is a valid representation of the physical SLS, as the differences between SLS and the simulation model are in the same order of magnitude. The calculated ratio between the required force to generate a luminaire reposition in the simulation model and the real SLS was in the range of 1.1 and 1.4 (Table 18).

Figure 57 - SLS configuration for measurement required force to reposition system.



Top view of the 2D surgical lighting system (SLS) pendant arm configuration at four luminaire positions to measure the required force to reach the threshold of motion of the SLS as a total.

Table 17 - The mean of measured forces at threshold of motion to initiate SLS luminaire reposition, N =3

Force direction	*Validation ratio at the each surgical lighting system configuration*			
	0 degrees (parallel)	*30 degrees*	*60 degrees*	*180 degrees (serial)*
X-positive	>> 100 (max)	80	58	32.5
X-negative	>> 100 (max)	80	61	32.5
Z-negative	34	27.5	27.5	>>100 (max)
Z-positive	34	27.5	32.5	>> 100 (max)

The force was measured for the SLS as a total in the 4 SLS pendant arm configurations of Figure 37. N = 3 for each individual force vector direction measurement.

Table 18 - Model validation measure as a ratio between required force to initiate luminaire repositioning in the model and physical SLS.

Force direction	*Validation ratio at the each surgical lighting system configuration*			
	0 degrees (parallel)	*30 degrees*	*60 degrees*	*180 degrees (serial)*
X-positive	1	1.2	1.4	1.1
X-negative	1	1.2	1.3	1.1
Z-positive	1.1	1.3	1	1
Z-negative	1.1	1.3	1.3	1

Model consistency

Model consistency was verified by repeating the validation simulations ten times and comparing the outcome. There was no variance detected in the model outcome during the ten different model simulation runs.

Model reliability

The reliability of the model was verified by assembling the model according to the MSC Adams tutorial [19] and subjecting the model to 4 debugging checks incorporated in MSC Adams with good results:

1. Inspection of the model visualisation, since ADAMS/View uses visual indication as for example broken screen icons to indicate error and joints or forces that are incorrectly defined;
2. Authentication of correct topology of the parts, constraints and forces (Appendix H);
3. Verification for non-existing error conditions in the model (Appendix I);
4. Verification of all individual functions expressions, used for the simulated joint friction behaviour.

5.4 Data output and analysis

The data output of the MSC Adams SLS simulated model was generated by implementation of a repositioning of the luminaire task assignment, based on the hypothesis defined in Paragraph 5.2. A 2Dimensional (2D) simulated map of required force - luminaire location was generated in the work field of possible repositions of the luminaire. The simulation data results were exported from MSC Adams to a Microsoft Excel tab file for data analysis and visualization in combination with Matlab version 7.

5.5 Validity, verification and reliability of the simulation method

Threat to the internal validity was the researcher bias. All the research steps were undertaken by the researcher (choice of simulation software, obtaining simulation input with measurements, the model creations software code, data output creation and result interpretation), which gives the risk of researchers own influence in the results. To minimize the influence two actions were made. Firstly the simulation modelling steps were defined so that others can repeat the simulation model assembling process. Secondly the research steps were defined in advance.

A bias of simulation method could be introduced by the selected outline of the simulation model: the employment of the MSC Adams as the simulation software or the four relatively simple model assumptions to construct a simulation model of the real SLS: (1) The SLS is a rigid multibody system; (2) The rigid body segments are slender rods; (3) There is no margin error in the 1 degree-of-freedom joint; (4) Joint friction behaviour is approximated with Coulomb's law of friction. Simulation runs in MSC Adams are a form of black box modelling, and another simulation software program might display a different outcome. In addition, more complex model assumptions will likely result in more detailed outcome of the simulation runs. These alternatives were not investigated in this dissertation as they were deemed premature for this exploratory research. But this bias would result in a low validity of the simulation model, for which an assessment of the selected model outline was obtained by composing a measurement of the simulation model validity (cf. 5.3.4) by comparing self-made measured of mechanical data of the real physical system with mechanical data of the model simulation runs.

Based on this validation procedure it was concluded that the selected simulation model outline was valid. The differences in mechanics between real SLS and the simulation model were in the same order of magnitude. Still, it is interesting to explore the effects of modelling assumptions with a higher detail. Although it is deemed prudent to be selective which model assumption, it is further explored, since it will be a trade off between improvement and further complexity. The physical SLS entails a joint with viscous friction behaviour and is therefore dependent on joint velocity, while the constructed simulation model only entails joints with non-viscous friction behaviour. This augmentation does not only require more complex modelling but also a more elaborate measurement procedure than used in this research, which in turn has consequence for the cost and time consumption. On the other hand, further detailing of the 1 DOF joint and application of rigid body dynamics is not recommended. No margin error was detected as the system joints were not sloppy during the applied force measurements and deformation of the SLS body segments is highly unlikely with the robust materials of the SLS. A more detailed modelling of the friction behaviour is deemed as an augmentation in future research, since the simulation model is valid only for low (angular joint) velocities.

The external validity is restricted to the one luminairy system brand of this study. Generalization of one individual luminaire must be done with care. The goal of the experiment was to gain a procedure to evaluate various different luminaries. The dissertation supplied a piece of a larger puzzle, so that in future research the simulation model will lead to mutually comparison of various SLS.

In software engineering model verification is a key aspect, which is concerned with building the model right. The verification of the model was achieved by construction of the model via the MSC Adams tutorial and debugging the model via the MSC Adams software. Threats to the model reliability were inaccurate approximated input parameters due to measurement errors or uncertainties in the measurement method. The sensitivity of the simulation model output on these factors were analysed with a sensitivity analysis, as presented in the next chapter. Reliability of the parameters was pursued by taking in consideration the identified measurement risks, which were described in Paragraph 5.3.2

5.6 Conclusion

This chapter illustrated the construction of a valid simulation model in MSC Adams of a Berchtold SLS, to allow virtual experiments with the luminaire to obtain insight into the mechanics of the system to clarify the obtained insights from the observation study. The simulation instrument was presented in three stages, by first determining the four model assumptions. Then model data were collected via measurements, after which the data were processed in the MSC Adams simulation software code. Finally the reliability, validity and consistency of the simulation model were verified. A self-composed measure of the validity indicated that the simulation model is reasonably valid, as the differences between SLS and the simulation model were in the same order of magnitude. Based on the formulated model assumptions, the simulation model is valid for low (angular joint) velocities. The simulation model of the SLS is now able to generate the required information.

6. SLS model simulation runs

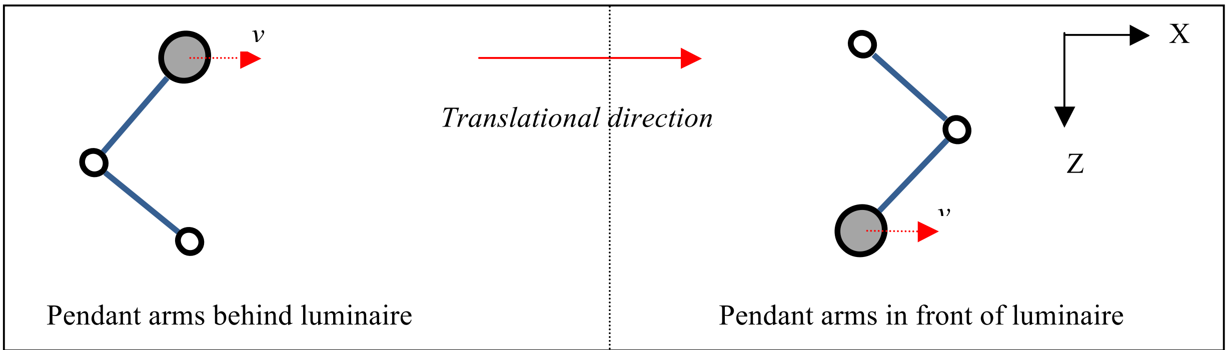
6.1 Introduction

This chapter presents the results of the simulation model of the SLS. Paragraph 6.2 presents the set up of the dynamic model simulation runs performed in MSC Adams, followed by Paragraph 6.3 with the results of the dynamic analysis. Paragraph 6.4 contains the conclusion of chapter 6.

6.2 The set up of the dynamic model simulations in MSC Adams

The constructed SLS model was used to perform simulation runs in which the luminaire was repositioned along a translational line under influence of an external applied force in the horizontal 2D plane of the pendant arms in the (1) total work field and the (2) central work field for possible repositions of the luminaire. The total work field entails the entire fields of possible LAs. The central work field entails the region in which most actions of luminairy repositioning were noticed during the observation study. Translations lines with the initial SLS configurations were defined in such a way that the force map contained information of SLS model luminaire repositioning based on the generally two different possible pendant arm configurations in relation to the luminaire: In one the pendant arms are behind the luminaire; in the other the pendant arms are in front of the luminaire in translational reposition (Fig 58).

Figure 58 - The two general SLS pendant arms configuration for luminaire repositioning in work field.



On the left side the pendant arms are behind the luminaire, on the right side the pendant arms are in front of the luminaire during the translational reposition

Simulation runs were translational repositioning of the luminaire along an axis in the work field, either along the various x or various z lines. During the x-translational simulation runs the z-coordinate of the luminaire location was held constant, during the z-translation the x-coordinate of the luminaire location was held constant. The velocity of the luminaire repositioning was held constant at 0.1 m/sec. during the x-translational simulation runs and -0.1 m/sec. during the z-translational simulation runs. Although an exact velocity measurement was not performed for the observed LAs during the observational study, the recorded images indicated that this velocity corresponded with the speeds of the observed LAs. The translational velocity speed had to be constantly low to maintain the validity of the simulation model; the application of the model assumption of Coulomb's law of friction; the neglect of inertia effects; and the performed measurement (at low constant velocity speeds). The information of the luminaire position and required translational forces was used to generate a contour plot of the required forces for luminaire repositioning in the SLS work field.

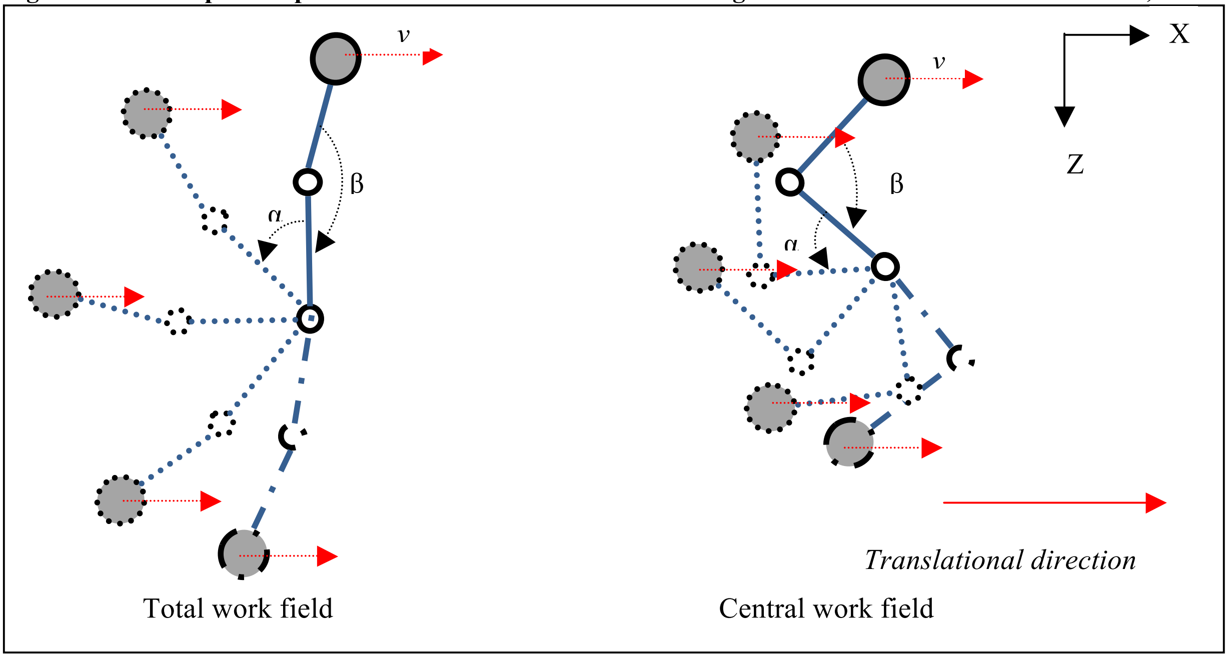
Each translational simulation was run until lock up of the system was detected, in which case MSC Adams would terminate the simulation run due to the fact that the model constraint(s) could no longer be satisfied, when the luminaire was at boundary of the modelled SLS work field. The initial SLS model configuration was depicted to overcome a system lock up (the so-called gimbal lock) at the initiation of the simulation run (Figures 59 & 61): Beta (β) was 170 degrees:

- Figure 59 depicts the initial system configurations for the first simulation run (outline in solid lines) and last simulation run (outline in dash dot lines), with in between three initial system configurations (outline in dashed lines) during certain in between simulation runs in both the total and central work field;
- Figure 61 depicts the same set up as Figure 59, only for the z-translational reposition of the luminaire. The initial alignment between the system pendant arms was denoted by beta (β).

Different x-translational lines were achieved by rotating the initial model configuration along and angle alpha (α) of ten degrees after each simulation run to obtain a total of N = 18 simulation lines (Figures 60 & 61).

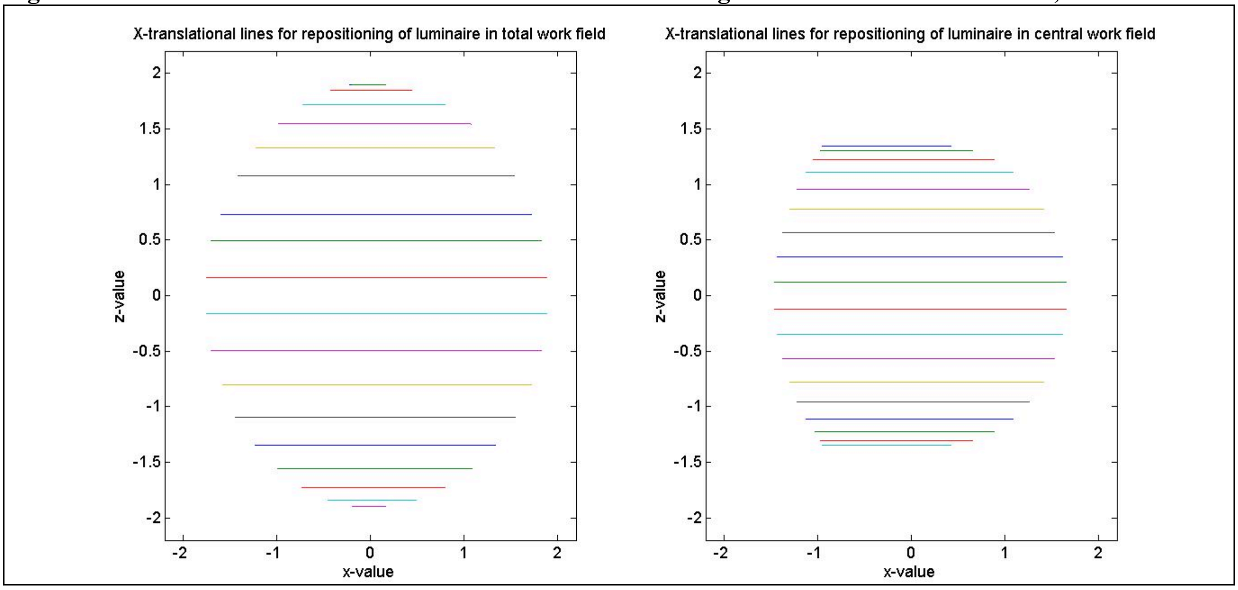
Translation lines during which an exact parallel alignment of the pendant arms would be reached were omitted in the generated force map. Inclusion of that data would produce a discontinuous image in the contour map, as the position vector of the luminaire has limited elements.

Figure 59 - Conceptual representation of SLS initial model configurations for X-axis simulation runs, N = 18



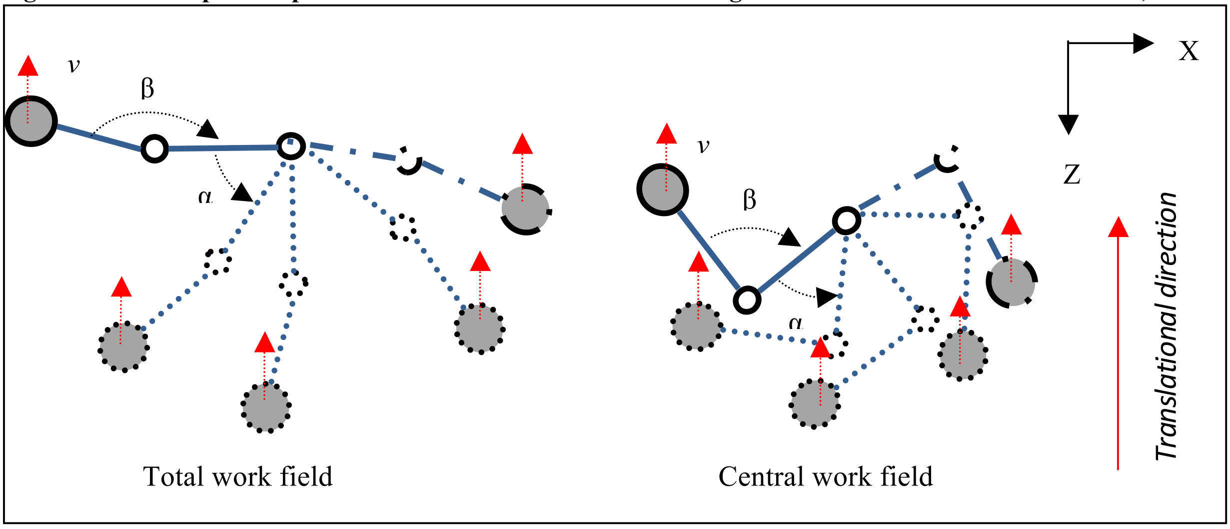
Above are shown 5 initial configurations of the SLS model. In total 18 simulation runs were performed with varying Z-values (N = 18). During the simulation run the model luminaire was repositioned along the X-axis in both the total as central work field. The initial system configurations for the first simulation run are outlined in solid lines, the last simulation run configuration is outlined in dash dot lines and three in between initial system configurations are outlined in dashed lines.

Figure 60 - The 18 translational lines of luminaire centre during each X-axis simulations run, N = 10.



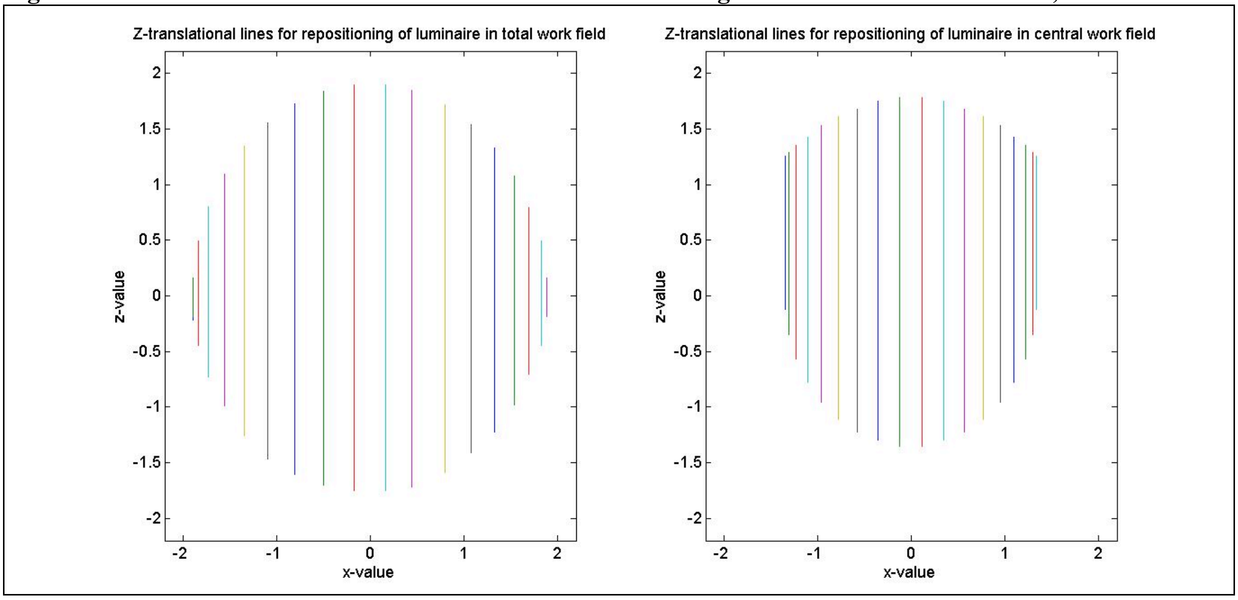
The left picture depicts the total work field, and the right picture the central work field.

Figure 61 - Conceptual representation of SLS initial model configurations for Z-axis simulation runs, N = 18



Above are shown 5 initial configurations of the SLS model. In total N = 18 simulation runs were performed with varying X-values. During the simulation run the model luminaire was repositioned along the Z-axis in both the total as central work field. The initial system configurations for the first simulation run are outlined in solid lines, the last simulation run configuration is outlined in dash dot lines and three in between initial system configurations are outlined in dashed lines.

Figure 62 - The 18 translational lines of luminaire centre during each Z-axis simulations run, N = 10.



The left picture depicts the total work field, and the right picture the central work field.

Table 19 - Time duration of the N = 18 simulation runs during the translational repositioning of the luminaire along both the X and the Z-axis in the total and central work field (see also Fig. 41 until 44).

Total work field			*Central work field*		
angle (α)	*X translation simulation duration*	*Z translation simulation duration*	*angle (α)*	*X translation simulation duration*	*Z translation simulation duration*
0	8.9	8.9	0	17.1	17.1
10	13.7	14.2	10	18.6	18.6
20	17.9	18	20	20.1	20.1
30	20.8	20.9	30	21.5	21.5
40	23.1	23.2	40	22.8	22.8
50	24.8	25	50	23.8	23.8
60	26.3	26.2	60	24.6	24.6
70	27.1	27.1	70	25.2	25.2
80	27.5	27.5	80	25.5	25.5
90	27.5	27.5	90	25.5	25.5
100	27.1	27.2	100	25.2	25.2
110	26.2	26.2	110	24.6	24.6
120	25	24.8	120	23.8	23.8
130	23.2	23.1	130	22.8	22.8
140	20.9	20.8	140	21.5	21.5
150	18	17.8	150	20.1	20.1
160	14.2	14.2	160	18.6	18.6
170	8.9	8.9	170	17.1	17.1

The step size in MSC Adams was 0.1 seconds, which represents the amount of time between output steps. The simulation data output were exported from to MSC Adams to a Microsoft Excel tab file. In Microsoft Excel the first and last column elements were deleted to eliminate the start and end behaviour of the simulation run. These elements are improper as they are the result of the MSC Adams numerical calculation of a discontinuous situation: The abrupt transition between zero and the constant velocity of the luminaire. The Microsoft Excel data sheet was in turn imported into Matlab version 7 to allow data processing and visualization of the acquired two dimensional force - luminaire location mapping. The required forces in the x- and z-directions during the luminaire translational simulations were computed into one resultant force, $Ft = [(Fx)^2+(Fz)^2]^{1/2}$. The forces in the data sample were maximised in Matlab at 600 Newton to limit the simulated forces of the model lock. In MSC Adams these force can reach extreme values before simulation is terminated. The Matlab programming code is presented in appendix J. Table 14 presents the simulation run times, arranged by alpha (α) of the initial SLS pendant arm configuration.

A force spectrum of the required force (Ft) for translational repositioning of the luminaire in the simulation model was calculated by presenting mean, maximum, minimum and standard deviation in three regions of the SLS work field, as defined earlier in this dissertation (c.f. 4.3.2 page 58):

- *Region1 = Central work field*: In this region the system pendant arms are (almost) in parallel configuration and the moment arm (L) is at max 47.5 cm., equal to the radius of the luminaire;
- *Region2 = Mid work field*: The luminaire is in the region between the central and peripheral field, and the angle between the pendant arm is in a range of: $47.5 \leq L \leq 187$ cm;
- *Region3 = Peripheral work field*: The luminaire is in the peripheral region. The pendant arms are (almost) in serial configuration, and L is in a range of: $190 \leq L \leq 190$ cm.

6.3 Result of the dynamic analysis with the software simulation instrument

The generated contour plot of the required forces for luminaire repositioning in the SLS work field displayed non-uniform force fields (Figures 63 & 64 and Appendix K[12]). The required forces for a luminaire repositioning in the work field of the SLS were also on average above the ergonomically acceptable level in the total work field (Figures 65 & 66). On the other hand, the force spectrum displays a very high variety for the three regions of the SLS work field:

- The maximum forces occur in the central and outer regions, which also display the highest diversity in the force spectrum;
- The minimum forces for all three regions are low, in the range of 14 - 26 Newton;
- The mid field region with an average force of 65 Newton and a maximum force of 117.5 Newton is the ergonomically the best acceptable work field region to perform a LA.;

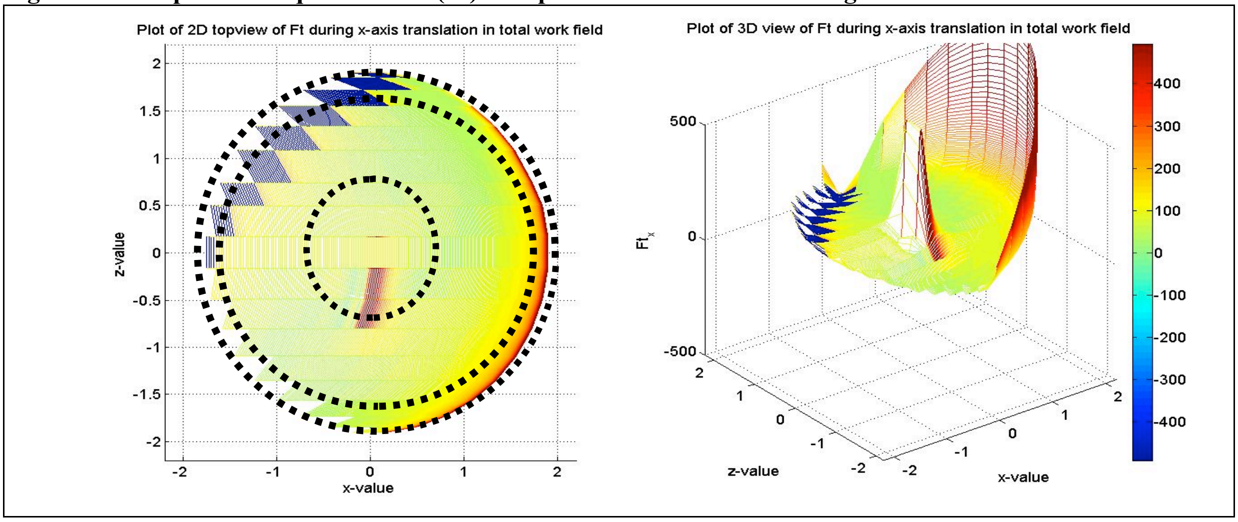
The simulation model thereby confirmed that the force to reposition the luminaire is dependent on the location of the luminaire in the work field. It also confirmed that the cause for this kinetic behaviour is due to the mechanism of the SLS of the system pendant arms. The highest force peaks were noticed at the centre of the work field, where the system pendant arms are in (near) parallel alignment. And in the peripheral region of the total work field, where the system pendant arms are again in a (near) gimbal lock due to (near) serial alignment.

Also, on average the required forces are higher than ergonomically acceptable. The ergonomically acceptable forces a human should exert on external bodies with his upper extremities (hand and arm) depends on the force direction and the location of the interaction between human and the body in relation to one own position: A LA performed at head heights and close proximity of the LP should be in the range of 28 till 62 Newton for forwards and backwards motions, or 11 or 13 Newton for inwards or outwards motion [7].

[12] Figure 63 gives the (required) force - luminaire location map of the luminaire repositioning along the x-axis, while figure 64 states an equal map, but only for the luminaire repositioning along the z-axis. In appendix K presents plots of the force - luminaire location maps, in which the (required) translational force to reposition the luminaire in both the x- and z-direction are given separately. Appendix K also presents the required force - luminaire location maps in both the total and central work field

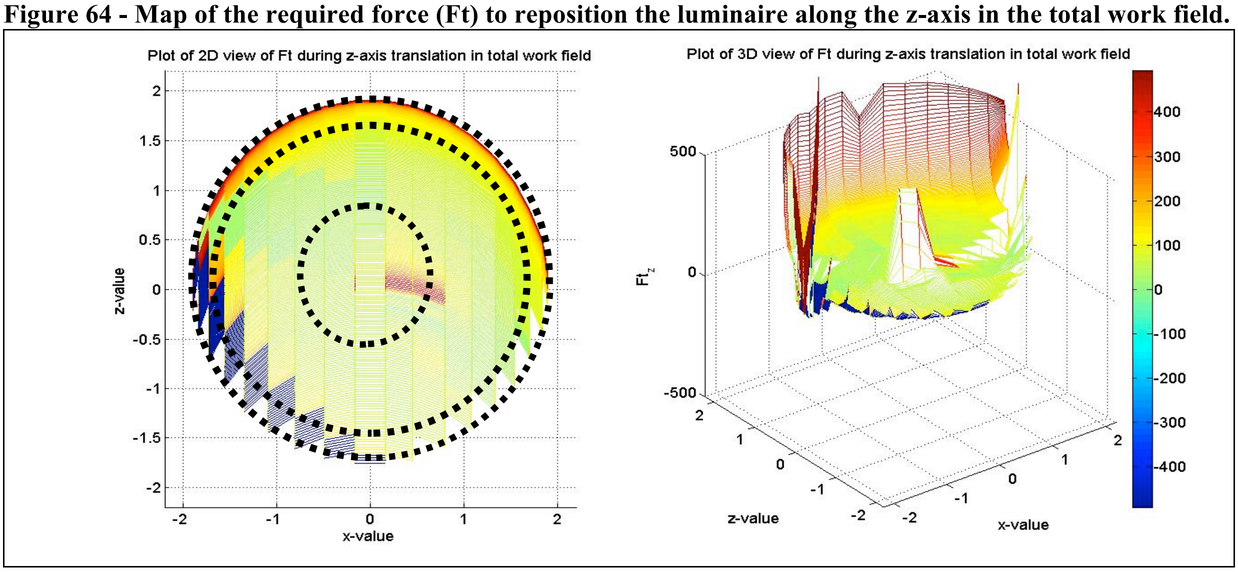
The combination of these two conclusions could be the explanation why the observed luminaire relocations did not take place along the shortest route in 3D space [10]. The user of the SLS will encounter a lower and ergonomically acceptable during the repositioning of the luminaire through the mid field region, that a reposition of the luminaire strictly in the central or peripheral work field.

Figure 63 - Map of the required force (Ft) to reposition the luminaire along the x-axis in the total work field.



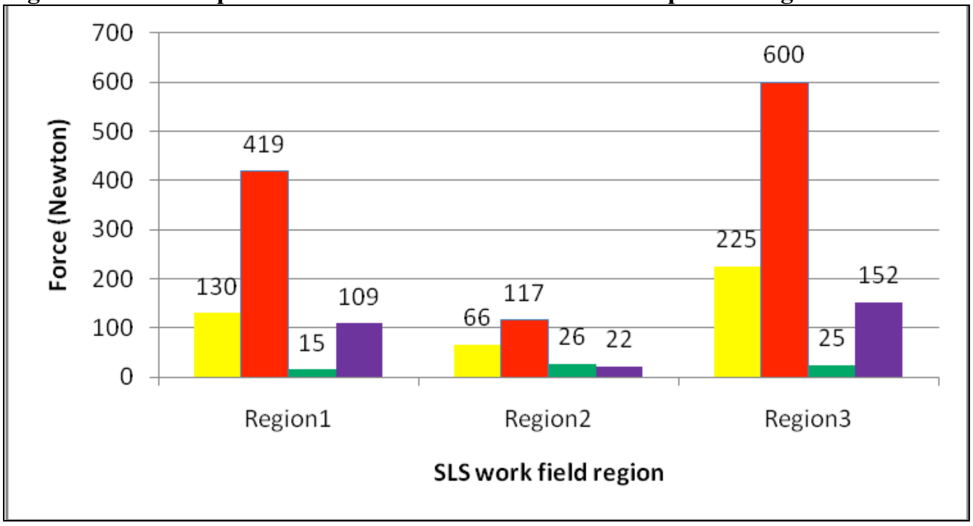
Map of the required force (Ft) to reposition the luminaire along the x-axis in the total work field. The vertical colour bar on the right indicates the force value scale of the map in the range of 500 until -500 Newton. In the left 2D map the three SLS work field were incorporated, as introduced on page 58 and Fig. 30. The boundary of the work field regions are formatted as the dashed black colour line.

Figure 64 - Map of the required force (Ft) to reposition the luminaire along the z-axis in the total work field.



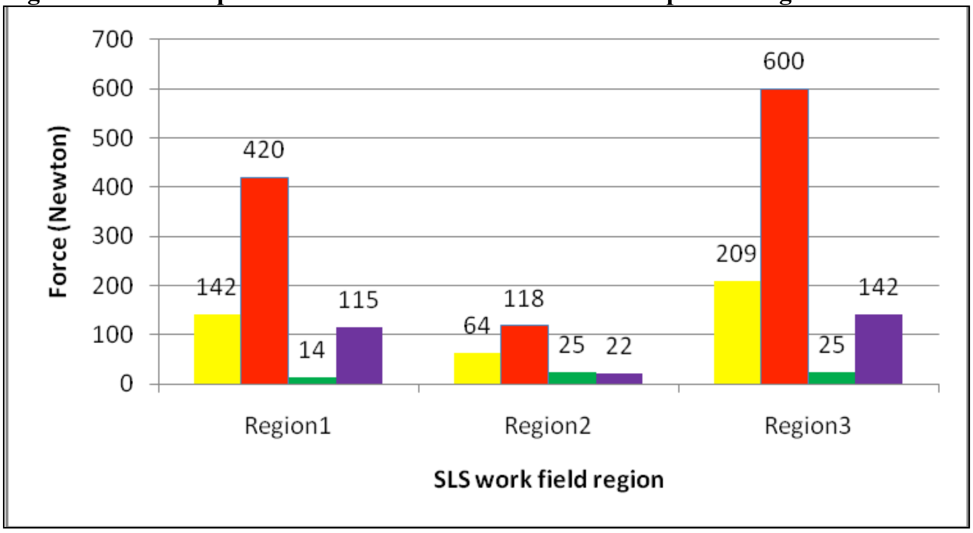
Map of the required force (Ft) to reposition the luminaire along the z-axis in the total work field. The vertical colour bar on the right indicates the force value scale of the map in the range of 500 until -500 Newton. In the left 2D map the three SLS work field were incorporated, as introduced on page 58 and Fig. 30. The boundary of the work field regions are formatted as the dashed black colour line.

Figure 65 - Force spectrum of X translational luminaire repositioning in work field



Mean (yellow column), maximum (red column), minimum (green column) and the standard deviation (purple column) of the required force (Ft) during the X translational repositioning of the luminaire in each SLS work field region (page 58 and Fig. 30).

Figure 66 - Force spectrum of Z translational luminaire repositioning in SLS work field



Mean (yellow column), maximum (red column), minimum (green column) and the standard deviation (purple column) of the required force (Ft) during the Z translational repositioning of the luminaire in each SLS work field region (page 58 and Fig. 30).

6.3.1 Sensitivity analysis of the SLS simulation model.

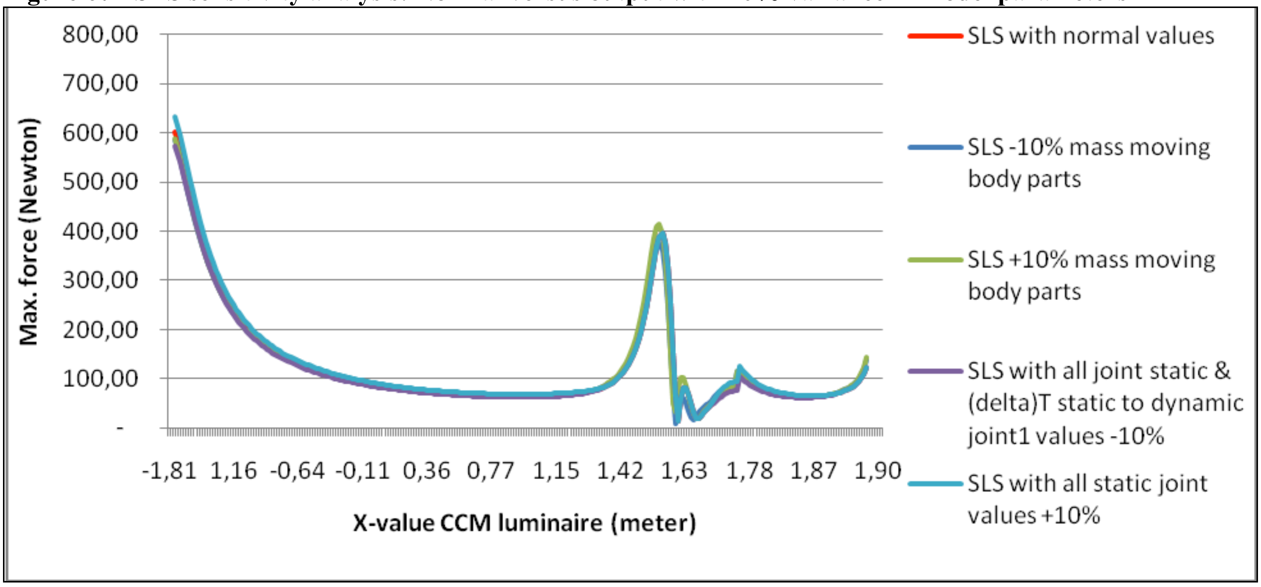
Earlier in study the necessity of a sensitivity analysis (SA)[13] was stated due the fact that certain model input parameters were approximated during the process of SLS model construction: (1) The mass distribution over the rigid body dynamics; (2) the resistance behaviour at the interconnecting joints. Besides, there was dispersion in the measurement data and the parameter values and assumptions of any model are subject to change and error. The SA procedure was performed to increase the confidence in the model by identifying the sensitivity or these variables and thereby determine the level of required approximation. The SLS model output was calculated while the approximated variables were adjusted with a variance of plus & minus 10% of its normal values.

The SA showed that possible errors and assumptions in the approximated parameters does not affect the significance of the the insights gained from the SLS model. The resulting output variance is less then 10% of the variance of the parameters (Fig. 67). A variance in the static resistance resulted into a slight change of force output, which is primarily due to resistance behaviour of joint 1. The variance in mass distribution of joint resistance behaviour resulted slight changes in force output order of magnitude, which is primarily due to the inertia of the luminaire (Appendix M).

In contrary with the above, an adjustment in the SLS pendant arm geometry that alters the SLS pendant arm length does have an impact on the SLS model force output. The length of the pendant arms was adjusted with a variance of 10% elongation or shortening. This alters the luminaire location in relation to the SLS central axis at the ceiling suspension. This analysis was performed to gain an additional insight in the SLS model, within the SLS work field regions. A transition from the central work field to the mid work field reduces the required force for a LA (Fig. 68).

Note that the tweaking of the SLS geometry, while imposing fixed translation lines for the luminaire repositioning, does induce the risk of imposing trajectories that will require - at some time - an impossible kinematic arrangement. That moment lead to a lock of the SLS simulation model and termination of the simulation run. This happened during the run of the SLS with shortened pendant arms at x location of the centre of mass at 1.15 meters (Fig. 68).

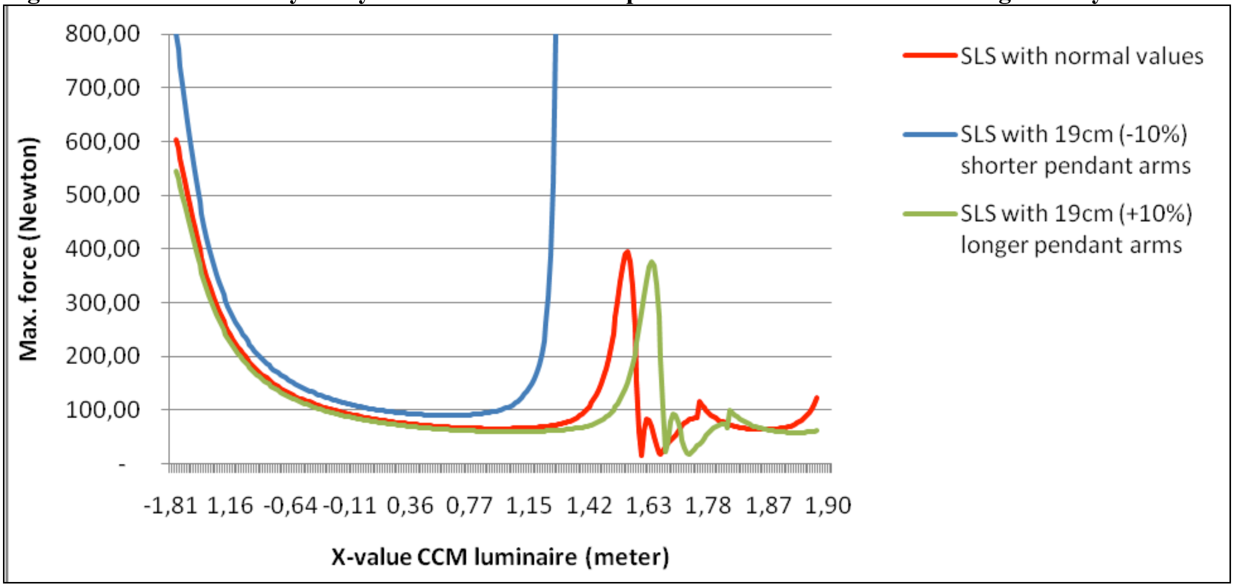
Figure 67 - SLS sensitivity analysis: Normal versus output with 10% variance in model parameters



The reference in the legend of SLS mass moving body parts include all the SLS body parts except the flange tube. This body part is statically fixed to the ceiling suspension.

[13] Sensitivity analysis (SA), broadly defined, is the investigation of these potential changes and approximation (errors) and their impacts on conclusions to be drawn from the model.

Figure 68 - SLS sensitivity analysis: Normal versus output with 10% variance in model geometry



6.4 Conclusion

This chapter presented the results of the MSC Adams simulation runs of a validate SLS model. The analysis confirmed the hypothesis (cf. Paragraph 4.5) that the required force for a luminaire repositioning is dependent on the location of the luminaire in the work field. High forces are noticed especially in the work field regions in which the SLS pendant arms are either in (near) serial or parallel alignment. These forces are an average also higher then ergonomically desirable. A sensitivity analysis of various model input parameters showed that the SLS model output was primarily sensitive to the geometry (length) of the SLS pendant arms. Based on these insights a possible improvement of the SLS should be found in the SLS mechanics by changing the kinetic relation between the system and user due to an adjustment of the system mechanical configuration of two pendant arms.

7. Discussion, conclusions and recommendations

7.1 Discussion

General discussion

This research study has presented new insight into the OR lighting problem during open routine surgical procedures in the field of general surgery, the construction of a valid SLS model of brand Berchtold and type C series in MSC Adams software, and it has presented a protocol to analyse the SLS using engineering software simulation. From that this dissertation has presented a direction for future research and an improved user system interaction of the luminaire during surgical procedures.

This dissertation showed at the start that the OR lighting problem is a signal of a deficient interaction between a user (medical staff member) and a system (SLS). Either (1) the surgeon capabilities (dexterity and system knowledge) are limited for proper control of the system, or (2) the system has suboptimal conditions that present limitations for a proper control to reach the desired end result. In the follow-up of this study the focus was to objectively describe the user-system interaction between the medical staff and the SLS during surgical procedures with an emphasis on the engineering side of the problem. Although the experience of the medical staff members was not included, it appears that the user has limited knowledge or need of the system capabilities due to the fact that only one interaction variable is used. This indication is worth a further investigation. But above all, an improvement of the SLS is deemed compulsory. The user is the expert in his field and the established environment and available instruments should support that expert as much as possible in order to execute the surgical procedure on the patient.

The observations study shows that the need for repositioning the luminaire during surgery is high, and that repositioning is cumbersome. The focus of improving surgical lighting systems should be on minimizing the need for repositioning the luminaire, and on minimizing the forces required for such actions. The simulation model confirmed that the force to reposition the luminaire is dependent on the location of the luminaire in the work field. Also, on average the required forces are higher than ergonomically acceptable. The combination of these findings could be the explanation why most observed luminaire relocations did not take place along the shortest route in 3D space. The observation study indicated, and the simulation model data confirmed, that the pendant arm system mechanism of the SLS is a bottleneck. Most LAs were performed by surgeons and residents, while they were performing surgical tasks. This is logic, as only they can judge when lighting is insufficiently directed or what improvement in illumination can be expected when the luminaire is repositioned. Therefore, it is wise that they are in command of the lighting system. However, it is undesirable that their attention is drawn away from surgery frequently, for an unnecessary long period of time or too intensively. Especially in crucial situations inadequate lighting or a cumbersome repositioning process to obtain a well-lit situation was reported to create potential hazards [22].

Although a solution to the problem has not been explored in this study, the focus should be an ergonomically better user system interaction with lower required forces for repositioning; the interaction between the user and the luminaire is minimized, or in specific the actions above the shoulder of the performer is prevented. When the need for luminaire repositioning arises, the surgeon should be able to perform this task with minimal effort and by paying minimal attention to this secondary task. With the currently available materials, the use of surgical headlights might improve lighting in some cases, but they have drawbacks in terms of comfort, mobility, and user-friendliness. The exploration of a SLS design with three or more pendant arm system is deemed interesting as a possible solution, since it omits the risk of a gimbal lock.

Attention should also be paid to the risk of collisions and entanglement of the luminaire or pendant with heads, other luminaires, or pendant arms. Especially in ORs with many pendant arms for various pieces of equipment these collisions and entanglements are problematic. Solving this problem is not straightforward. A lighting system without pendants would tackle this aspect, but would induce reduced mobility and flexibility of the system, causing many situations hard to illuminate. A robotic, intelligent pendant system on the other hand, could avoid collisions when repositioning the luminaire; however, this increases complexity and costs. Further analysis on collision prevention is required.

In addition, the software engineering model which was constructed in this study is applicable as a test procedure to analyse current SLS of prototypes of future designs. In this study the simulation model of a Berchtold SLS was constructed in MSC Adams software, but it can be employed on other SLS as the presented model construction method supplied a valid and reliable simulation model.

Discussion points concerning the generalization of this study

The scope of the observation study data sample affects the external validity of this research, as was discussed in Paragraph 3.6. From a qualitative perspective, conclusions can only be drawn for the surgical procedures in the data sample at the Reinier de Graaf Gasthuis hospital with a SLS of the brand Berchtold and type C series, for routine surgical procedures in the field of general surgery. The question arises whether the selected data sample is representative for the larger field of surgical procedures. It is likely that a larger dataset will show similar characteristics of the OR lighting problem established in this research, since the user system interaction in generals entails the same three interaction variables.

There could be a difference in the intensity of the OR lighting problem and the effect on the course of the surgical procedures. This difference can be higher or lower. In the current data sample the medical staff members are not strained to their maximal abilities during the observed surgical procedures. It is possible that during that type of surgical procedure a surgeon has less leeway to perform a LA in surgical procedures beyond the current data sample and that the negative effect of difficulties during the user SLS interaction is higher during a complex surgery. The longest observed LA, due to a complicated interaction, was almost 38 seconds. This time duration could be fatal in the event of a life threatening incident during a 'complex' surgical procedure. Concurrently, the demands of the medical staff on the SLS are possibly higher due to the complexity, which also could lead to higher period of LAs.

Discussion points concerning the observation method

The discussion concerning the observation method was excessively done Paragraph 3.6. A number of possible limitations to the consistency and trustworthiness of the method and its result were identified: observation transfer; observation paradox; researcher bias. Countermeasures were successfully taken for these limitations.

Discussion points concerning the model simulation of the SLS

The discussion concerning the SLS simulation model was presented in Paragraph 5.5. Possible limitations to the consistency and trustworthiness of the method were due to the simplification of the reality and the approximation of certain model parameters. Therefore two validation procedures and a sensitivity analysis were implemented to verify that a valid and reliable SLS model was constructed.

7.2 Conclusions

This research was focused on the problems that medical staff members encounter with the OR lighting during surgical procedures. The primary goal of this study was to gain insight into the user-system interaction between members of the medical staff and the SLS during procedures in the field of general surgery, and consequently clarify the cause of the OR lighting problem. With the acquired insights the third goal of this thesis was the future improvement of medical instruments by indicating possible improvement of surgical lighting systems with the acquired insights of this dissertation. This dissertation adopted the methods of perioperative observation and software simulation.

The OR lighting problem is a perception of a deficient interaction between a medical staff member and the SLS to reach the desired result. It arises due to either the suboptimal system or the inaptitude of the user (or a combination of these two). Therefore, the problem is in fact a control issue during a user system interaction. Due to limited insights, the scope or the solution of the problem is not at hand. The available scientific papers only state the surgeon's perception of the problem. Insight into the interaction between the medical staff member and the SLS during surgical procedures is necessary to fill in the knowledge void. This study, as an engineering research, was focused on the system.

To effectively illustrate the user and the SLS interaction during a surgical procedure, the perioperative observation method was used. It is a qualitative research methodology, and is the only research method to gain objective information of the user-system interaction during surgical procedures. The data were collected during a direct non participant observation study of open routine surgical procedures in the field of general surgery. The location of the observation study was the Reinier de Graaf Gasthuis hospital in Delft, which uses the Berchtold C series as the SLS.

Under the assumption that the data sample gives a representation of the user system interaction during surgical procedures of open surgery, the surgical lighting problem was indeed noticed. This confirmed the findings from earlier survey research. In addition, this research has also contributed specific characteristics of the problem. In 45 hours and 8 minutes of surgery 364 LAs were noticed, resulting in an average period of one LA every 7.4 minutes. The interaction between the medical staff member and the SLS was purely a repositioning of the luminaire. The light beam's focus and the illumination levels were never adapted by the medical staff members during the observation period. Of these LAs, 74% was performed by surgeons and residents who are principal staff members responsible for the successful outcome of the surgical procedure. For 64% of these LAs the surgical tasks of OR-staff were interrupted. The dataset of the LA time duration was not homogeneous due difficulties that lead to some extreme long interaction time duration.

Observed difficulties were collision of the luminaire against any object, or that the luminaire was out of reach for the surgeon in a sitting posture. The primary difficulty appeared in the kinetic relation during the SLS and user interaction in the 2 dimensional plane of the pendant arms; it was observed that the LP sometimes could not reposition the luminaire; that the luminaire relocations did not take place along the shortest route in 3D space; or that the performer had to apply full force or undertake an oscillating action to start the movement. The difficulties resulted into longer time duration of the LAs in comparison to the observed LAs without difficulties or distracted the medical staff members from the operational activities of the surgical procedure. It appeared that the SLS loses a degree-of-freedom during some of the observed interactions, when the pendant arms are in configuration of parallel or serial alignment. This situation was therefore labelled as a SLS gimbal lock. It was hypothesized that the severity of the observed problem is related to the location of the SLS luminaire so that the required force for a LA is dependent of the luminaire location in the work field. In addition, it was beneficial to obtain an impression of the range of the required force for a LA.

This hypothesis was verified by a virtual experiment with a self constructed valid simulation model of a SLS. The simulation data illustrated that the required force to generate a LA is dependent on the location of the luminaire. The highest forces to generate luminaire reposition were found when the luminaire was directly below the ceiling suspension, or when the luminaire was in the peripheral region. In those two regions, the pendant arms configurations are either in parallel or serial alignment. A sensitivity analysis of various model input parameters showed that the SLS model output is primarily sensitive to the geometry (length) of the SLS pendant arms. These findings confirmed that the current systems mechanism with the two pendant arms is a cause of difficulties.

And the required forces are on average higher than ergonomically acceptable. The force spectrum to generate a LA action was at average +/-136 N. in central work field, 65 N. in mid work field and 214 N. in the peripheral work field (c.f. 4.3.2) but show a high variety in quantity as seen in the difference between maximum (600 N.) and minimum value (14 N.) and the standard deviation of the forces. From an ergonomic point of view, the acceptable forces a human should exert on external bodies with his upper extremities (hand and arm) depends on the force direction and the location of the interaction between human and the body in relation to one own position [7]. A LA performed at head heights and close proximity of the LP should be in the range of 28 till 62 Newton for forwards and backwards motions, or 11 or 13 Newton for inwards or outwards motion.

In addition, a valid simulation software engineering model was constructed of a Berchtold SLS in MSC with the defined model protocol that allows the virtual experimenting with a SLS to obtain the force position data of other systems.

7.3 Recommendations for future research

General recommendation

Repetition of this research by another scientist to verify the conclusions of the dissertation. The prime limitation of this research is the risk of researcher's own involvement in this explorative study as a sole scientist and therefore introducing bias and transfer in the research methods. As a research in the phase of exploration, the researcher defined the direction of steps for data collection, analysis and interpretations. Without a co-researcher or similar studies the possibility exists of modifying the results to the desired outcome, although actions were taken to certify that the research was unbiased. This recommendation has been made applicable due to the detail description of the research methods and the recording of the research data.

Recommendation for the improvement of the study during the repetition of this research

Include a medical specialist for the interpretation of the research data.
This research was performed by an expert in the field on mechanical engineering, exploring a problem perceived by medical specialist. The researcher is not an expert in the field of medical science. The involvement of a medical specialist will possibly improve the interpretation of the observation data; increase the formulations of pragmatic solutions to reduce the OR lighting problem. At last, the involvement of a medical specialist as a co-researcher might as well reduce the risk of researcher bias.

Include subjective data about the user system interactions among medical specialists.
The medical staff member perceives the interaction with the SLS as problematic, while their interpretations are not included in this study. And threat to internal validity of this research is the bias due to observation transfer: the researcher transfers his own interpretations of whether the user system interaction is a problem. It is possible that the subjective problem is different than the insight gained from this research. This shortcoming depends on the degree to which the interpretation of a problematic interaction has mutual meanings between a medical staff member and the researcher. Inclusion of subjective data among medical staff members about the OR lighting problem will increase the validity.

Improve the simple and manually performed joint friction behaviour measurements.
The manual controlled measurements were simple of nature, due to practical and economic limitations to save time, money and the fact that it had to be applicable on in use SLS. The measurement protocol induced approximation in the modelling steps. Even though a valid and reliable model was constructed, it is only valid for constant low angular joint velocities. In that region the mass moment of inertia and viscous friction behaviour of the hydraulic joint can be neglected. Improvement of the joint resistance behaviour measurements will increase the range of applications of the simulation model

Recommendation for additional research:

Extend the research data sample
Due to the data sample, conclusions can only be drawn for the surgical procedures in the data sample at the Reinier de Graaf Gasthuis hospital with a SLS of the brand and type Berchtold C series. Although is to be expected that a larger dataset will show similar characteristics of the OR lighting problem as concluded in this research, the external validity of the study results can be extended by a larger dataset incorporating multiple hospitals and more types of surgical procedures within the field of invasive surgery, and the construction of simulation models different from the Berchtold C series

Perform an investigation among medical staff members to obtain subjective data
Both to increase the efficiency and to acquire subjective information during the subsequent research, it is recommended to perform an investigation among medical staff members. The focus of the additional research should be on the question if the characteristics and intensity of the noticed OR lighting problems in this study vary between certain types of surgical procedures. This can be done by the research methods of interviews or surveys. In this way insights can be obtained of surgical procedures in which the observation method is not applicable (for instance due to sterile restrictions or emergency level), or will present possible information to enlarge the data sample in an effective manner and will overcome the limitation of this research which only required objective data on a subjective problem.

Explore the reason why medical staff members do not use full capacity of SLS.
During the observation study it was noticed that two of the three variables, that define the scope of the user system interaction, were not adjusted. The interaction between the medical staff member and the SLS was observed as purely a repositioning of the luminaire, and the light beam's focus and the illumination levels were never adapted. This dissertation did not collect data for the motive behind this observation, which makes the conclusion open for speculation.

Recommendation for the improvement of the SLS

Explore potential SLS mechanism improvements that change the kinetics of the luminaire, via the presented model simulation protocol
This research has indicated that there is a bottleneck in the mechanism of the SLS, resulting in a suboptimal kinetic relation between the system and user. The two primary criteria to improve the SLS are therefore the SLSs possible manoeuvrability (luminaire trajectory) and minimizing required force to generate a reposition of the luminaire. Also, the need for frequent luminaire repositioning will have to be reduced, and in specific the actions above the shoulder of the performer should be prevented.
The simulation model protocol which was formulated in this research provides a procedure to explore future designs. In that way, surgeons will be able to concentrate on their main task, and perform surgery in a well-illuminated wound by a more user-friendly SLS.

Construct a physical surgical prototype based on an improved design,
At this stage of exploration of the OR lighting problem, the construction of a physical prototype was undesirable before thorough simulation because of the involved risks and the strain on the medical staff. Although virtual prototyping is especially useful in the conceptual design stage to reduce the amount of physical testing that is required, it does not alter the current situation during the medical procedures. The construction of the physical prototype is recommended for future research, in which the design is improved based on the findings of this research.

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Appendix A - TU Delft project: LIFE-OR

Background of project
In modern surgery there is a large number of equipment that has to be positioned and controlled in the OR. Not only the operating table, the operation lamp, and anaesthesia equipment, but also instrumentation associated with new techniques such as gas- and insufflations equipment (laparoscopic tower), a variety of dissecting instruments and audiovisual facilities. A problem frequently associated with the OR is the ‘spaghetti syndrome” a situation which is often not shown on commercial pictures. A multitude of wires, tubes, and cables tangle and obstruct movable equipment and hamper the OR personnel in their movements and position. These circumstances make the OR a very complex technical surrounding to work in.

Project goal ‘LIFE OR’
The goal of this project is to design a human friendly LIFE (Lighting & Instrumentation- Flexible & Ergonomic) integrated system for controlling lighting and equipment in the OR. Novel techniques and methods such as, task- and error-analysis methods and 3D simulation of the OR make it possible to fundamentally evaluate possible solutions to the above mentioned problems. A breakthrough in the human friendly LIFE-system for controlling lighting and equipment in the OR is seen as possible in the near future. The result will be a well-organized workplace, making surgery safer.

*‘LIFE OR’ Project part of TU Deft research field ‘MISIT’*LIFE OR is one of the research project within the research field of ‘OR Equipment’, which is in return one of the main research fields of Minimally Invasive Surgery and Interventional Techniques (MISIT) lead by prof.dr. Jenny Dankelman. The reason for the relative new research field is that the continuous growth in popularity of minimally invasive techniques broadens the field of surgical applications, but also demands for new innovative instruments and guaranties of medical safety. Using a clinically driven approach, MISIT of the Delft University of Technology aims to improve minimally invasive techniques through the development of new instruments and training devices.

See further: www.misit.nl

Appendix B - Observation data score list, including the used definitions

General information of the setting surgical procedure

- Location hospital; surgical lighting system brand and type; operation date; operation room code / number; type of surgical procedure; number of medical staff members present at surgery

Score list during surgical procedure

- Duration of the surgical procedure from initializing until finalizing phase;
- Action on which surgical lighting system variable;
- Type of action: Manipulation or correction action
- Phase of the surgical procedure at time of action;
- Action on which luminairy: satellite / main light
- Time moment of the action;
- Time duration of the luminaire action;
- Reason for the action;
- Function of the performer of the action;
- Number of performers required to perform a LA;
- Is performer of action also the medical operator;
- Posture of the LA performer: standing or sitting;
- Focus of the performer throughout the action;
- Performer performs the LA with the use of one or two hands;
- Visible ease of the LA, divided by
  (1) Shortest route in 3D space or not;
  (2) Smooth or 'non smooth' action;
- Repositioning action is rotation, translations or rotation and translation of luminaire;
- Any additional comments on the LA.

Definitions

- Luminairy action: Action that results in adjustment SLS variable. Two types of action were defined:
  1. Manipulation: The action during which the SLS variable is adjusted
  2. Correction: The action during which the SLS variable is adjusted together with the condition that this action is performed after a manipulation action while in the meantime no operational activity was undertaken by the performer.

- The surgical lighting system has three variables: (1a) The luminaire focus, which affects the size of the diameter of illuminated field; (1b) The lighting illumination level, which affects the intensity of the light beam; (2) Reposition of the luminaire,

- Time duration of the luminaire action is defined as the moment that the LP initiates an activity of the upper extremities to begin the LA and ends as the LP continues his original task

- Reason for the action: change of the work area of the surgical activity; change of point of view medical operators; no illumination / shadow in the work space; no contrast in the work space tissue; bright light; light reflection on tissue or surgical instruments; out of focus work area for instance due to the repositioning of the table or the patient.

- Visible ease of the LA, divided by
  (1) Luminaire repositioning takes place along the shortest route in 3D space is defined from trajectory at start luminairy action until end of the action;
  (2) a LA is 'non smooth' if the performer had to apply full force or undertake a oscillating action to start the movement; and, finally any additional comments on the LA;

- Luminairy performer: Member of the medical staff who undertakes the action on the system

- Medical operator: The medical staff member that performs a surgical activity, that is not intended to control bleeding, suturing or provide wound exposure.

- Stage of the surgical procedure, 3 phases are defined to complete a medical operation:
  1. Initializing: This initial stage starts when the luminaire is turned and the operation is about to start – all medical staff members are in their required position as depicted in Figure 1, but no surgical activity (incision) has taken place yet.
  2. Surgery: The physical intervention of surgery on the patient's tissue is defined in 3 subparts:
     I. Opening - from first incision to the placement of retractors;.
     II. Operating - from placement of retractors until removal of the retractors. This is the stage in which the objective of the surgical procedure is carried out in the wound.
     III. Closing – from removal of the retractors until the last stitch;
  3. Finalizing: The surgery is finished. In the final stage the wound is closed, but still some finishing actions to the patient are being performed. The surgical procedure is finished when the last bandage over the closed wound is applied by a medical staff member.

Appendix C - Mechanical data of the SLS rigid body parts

The MSC Adams model of the surgical lighting system is presented in Figure 69 and has six rigid body parts: (1) flange tube, (2) horizontal swivel arm, (3) vertical tube, (4) hydraulic arm, (5) horizontal arm and (6) luminaire.

The element with the green colour is the ground part and functions in MSC Adams as a base part on which the model was connected to the 'real world'. In Table 15 are presented the geometry and mass information of the SLS simulation model, added with the number of segments from each body part and the used body type in MSC Adams to construct the model.

Figure 69 - SLS model outline in MSC Adams

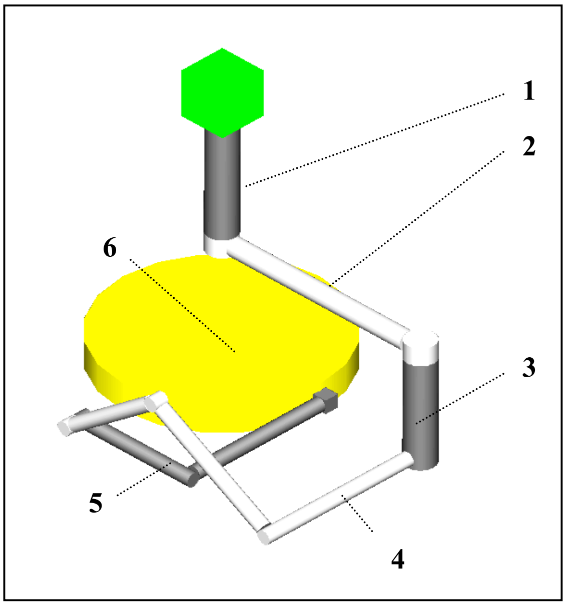


Table 20 - Geometry and mass distribution of the six rigid body parts of the MSC Adams model.

Rigid body part	*Segment nr.*	*MSC Adams rigid body type*	*Dimension of part (m.)*	*Mass (kg)*
1 - Flange tube	Segment1	Cylinder	0.51 * 0.0625	21.9
2 - Horizontal swivel arm	Segment1	Cylinder	0.08 * 0.0625	3.4
	Segment2	Cylinder	0.83 * 0.64	14.6
	Segment3	Cylinder	0.08 * 0.0625	3.4
3- Vertical flange tube	Segment1	Cylinder	0.6275 * 0.03	19.7
4- Hydraulic arm	Segment1	Cylinder	0.625 * 0.03	6.2
	Segment2	Cylinder	0. 57 * 0.03	4.8
	Segment3	Cylinder	0.06 * 0.03	0.5
	Segment4	Cylinder	0.375 * 0.03	3.2
	Segment5	Cylinder	0.06 * 0.03	0.5
5- Horizontal arm	Segment1	Cylinder	0.06 * 0.03	0.7
	Segment2	Cylinder	0.39 * 0.03	4.4
	Segment3	Cylinder	0.54 * 0.03	6.1
	Segment4	Box	0.06 * 0.06 * 0.06	0.9
6 - Luminaire	Segment1	Cylinder	0.12 * 0.475	25.5

Appendix D - Calibration data of the force sensor

The force sensor of type ZFA loadcell 100 kg was calibrated using various weights (kilograms): 0 kg.; 8.7 kg.; and 18.7 kg. This calibration resulted is the calibration Figure 70, and calibration function of: Force [Newton] = (Sensor output [Voltage] -0.03)/0.04. The specifications of the sensor are given in Table 21.

Figure 70 - Calibration of sensor type ZFA loadcell 100 kg

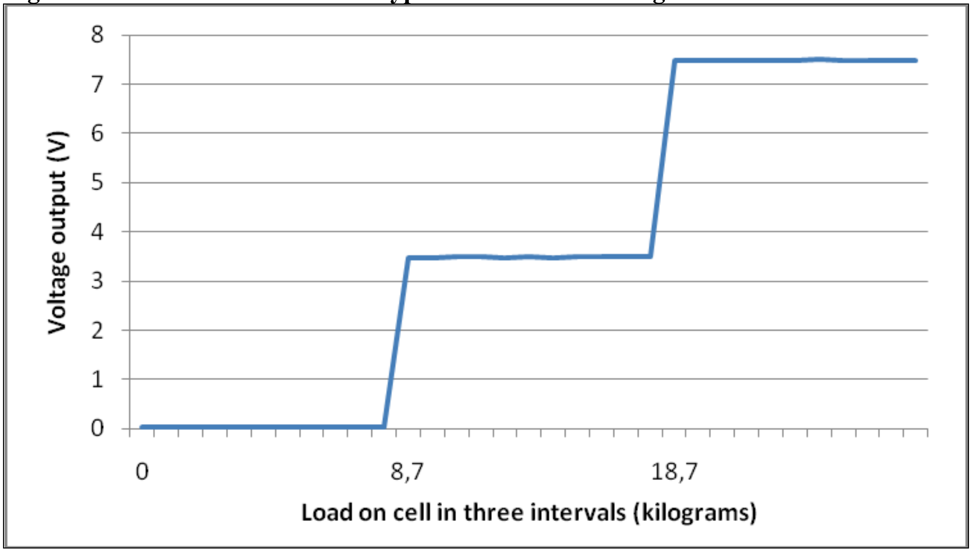
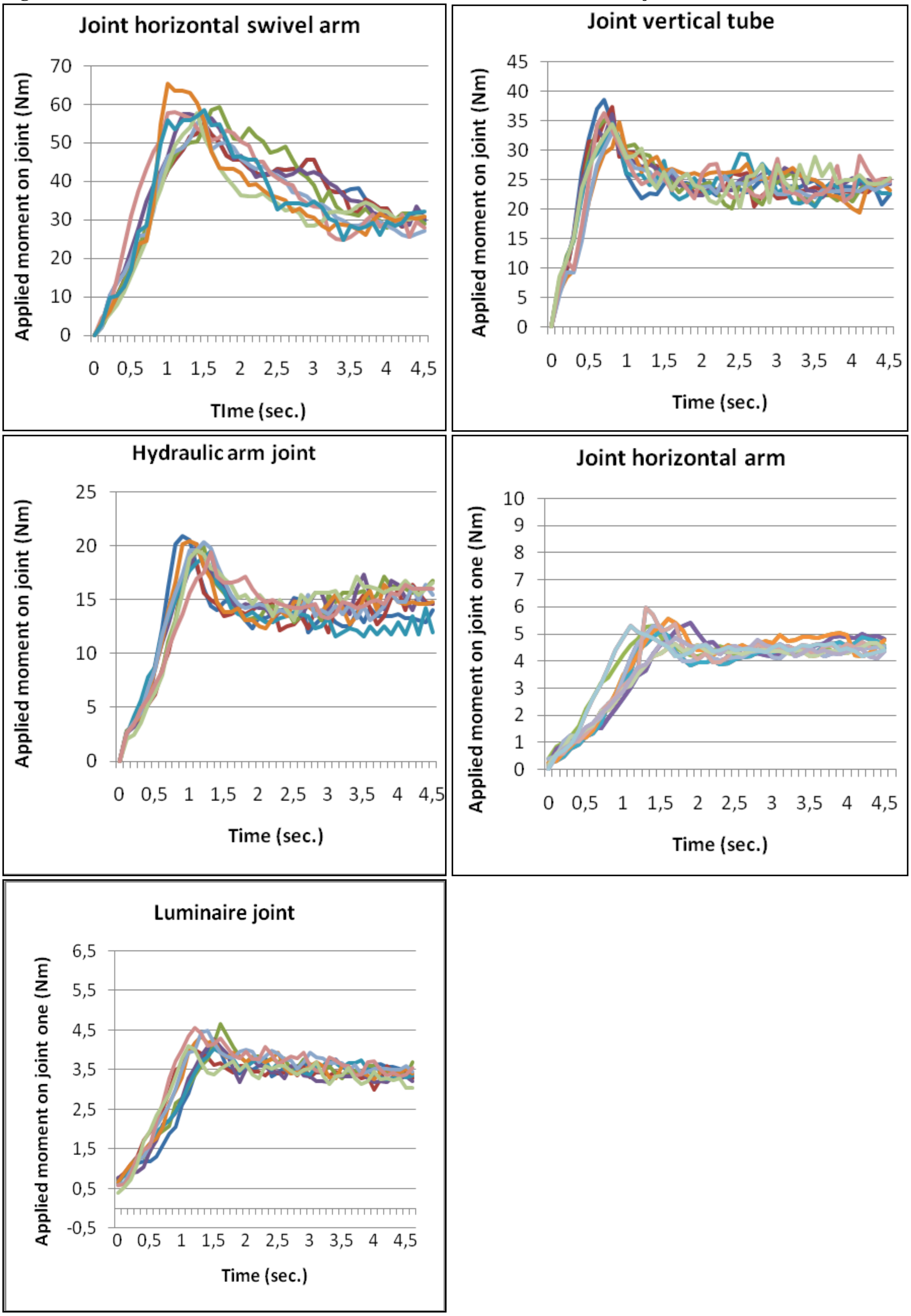


Table 21 - Specifications of sensor ZFA loadcell 100 kg

Capacity	100kg
Combined error	≤0.02%FS
Sensitivity	2.0±0.1%mV/V
Zero balance	≤1.0%FS
Non-linearity	≤0.02%FS
Repeatability	≤0.02%FS
Hysteresis	≤0.02%FS
Input resistance	380Ω
Output resistance	350Ω
Insulation resistance	≥5000MΩ(50VDC)
Temperature effect on sensitivity	≤0.020%FS/10℃
Temperature effect on zero balance	≤0.020%FS/10℃
Recommendatory excitation voltage	10V(DC)
Nominal range of excitation voltage	6~12V(DC)
Operating temperature range	-30~+70℃
Safe overload	120%FS
Material	Alloy steel/Stainless steel/Aluminium
Criterion	GB/T 7551-1997 / OIML R60:1991

Appendix E - Resistance data of the SLS joints

Figure 71 - Measured resistance data of each of the five individual SLS joints



Appendix F - Topology of the SLS simulation model

Ground Part: ground
There is one fixed joint to connect the model to the ground part.
1. Flange_tube_joint_fixed_arm connects flange_tube with ground
There are 5 revolute joints that connect the 5 body parts of the surgical lighting syste,
1. Horizontal_swivel_arm_joint connects Flange_tube with horizontal_swivel_arm;
2. Vertical_tube_joint connects horizontal_swivel_arm with vertical_tube;
3. Hydraulic_arm_joint connects vertical_tube with hydraulic_arm;
4. Horizontal_arm_joint connects hydraulic_arm with horizontal_arm.
5. Luminaire_joint connects horizontal_arm with luminaire;
There are 5 single force components to simulate the friction torque at each individual joint:
1. Horizontal_swivel_arm_friction_torque connects Flange_tube with horizontal_swivel_arm;
2. Vertical_tube_friction_torque connects horizontal_swivel_arm with vertical_tube;
3. Horizontal_arm_friction connects hydraulic_arm with horizontal_arm;
4. Hydraulic_arm_friction_torque connects vertical_tube with hydraulic_arm;
5. Luminaire_friction_torque connects horizontal_arm with luminaire
There are 5 single force components to simulate the applied torque at each individual joint:
1. Horizontal_swivel_arm_applied_torque_estimated connects Flange_tube with horizontal_swivel_arm;
2. Vertical_tube_applied_torque connects horizontal_swivel_arm with vertical_tube;
3. Horizontal_arm_applied_torque connects hydraulic_arm with horizontal_arm;
4. Hydraulic_arm_applied_torque connects vertical_tube with hydraulic_arm;
5. Luminaire_applied_torque connects horizontal_arm with luminaire;

Appendix G - Description of the MSC Adams STEP function

STEP approximates a step function with a cubic polynomial. It returns an array of y values, on a step curve, corresponding to the independent array of values (A). The function expression can be called by any user-written subroutine and does not require any prerequisite. The for The format of the calling sequence is STEP(A, xo, ho,x1,h1). The input arguments of MSC Adams STEP function are presented in Table 22, and the diagram outline in Figure 72.

Figure 72 - Outline of STEP function to explain the arguments of the function expression

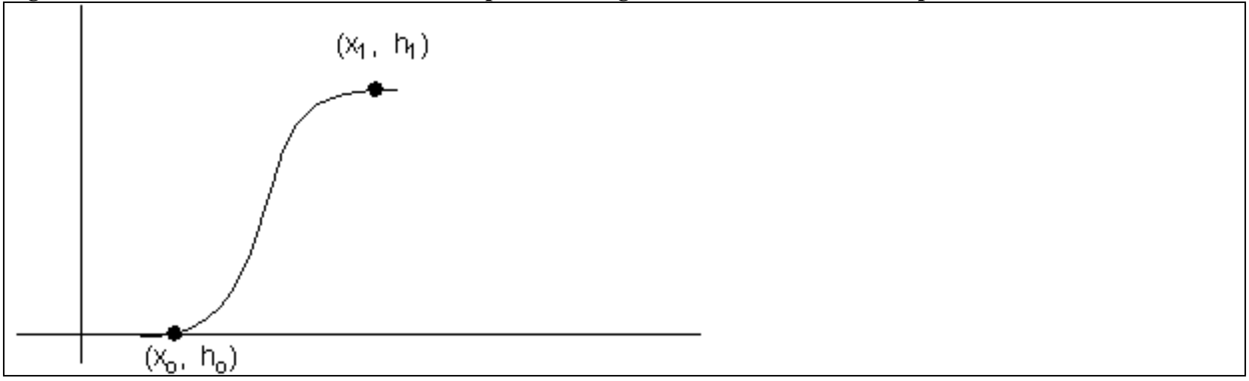


Table 22 - Input arguments of MSC Adams STEP function

A	An array of x values.
xo	Value of x at which the step starts ramping from ho to h1.
ho	Value of h when x is less than or equal to xo.
x1	Value of x at which the step function reaches h1.
h1	Value of h when x is greater than or equal to h1.

Caution: The value x1 must not equal x0. Equal values of x1 and x0 imply a discontinuous step, which STEP cannot fit.

Appendix H - STEP function expressions for model joint resistance behaviour

There are 5 single force components that generate the friction behaviour of each individual joint:

Horizontal_swivel_arm_applied_torque connects Flange_tube with horizontal_swivel_arm
+1.0*STEP(.surigcallightingsystem.horizontal_swivel_arm_joint_omega_z,-0.1 , 53.25 , 0.1, -53.25) +1.0*STEP(.surigcallightingsystem.horizontal_swivel_arm_joint_omega_z, -11.55 , -22.45 , 11.55, 22.45)
Vertical_tube_friction_torque connects horizontal_swivel_arm with vertical_tube
+1.0*STEP(.surigcallightingsystem.vertical_tube_joint_omega_z, -0.001 , -33.4 , 0.001, 33.4) +1.0*STEP(.surigcallightingsystem.vertical_tube_joint_omega_z, -0.03 , 9.5 , 0.03, -9.5)
Hydraulic_arm_friction_torque connects vertical_tube with hydraulic_arm
+1.0*STEP(.surigcallightingsystem.hydraulic_joint_omega_z, -0.01 , 18.4 , 0.01, -18.4) +1.0*STEP(.surigcallightingsystem.hydraulic_joint_omega_z, -0.03 , -5.3 , 0.03, 5.3)
Horizontal_arm_friction connects hydraulic_arm with horizontal_arm
+1.0*STEP(.surigcallightingsystem.horizontal_arm_joint_omega_z, -0.01 , -4.75 , 0.01, 4.75) +1.0*STEP(.surigcallightingsystem.horizontal_arm_joint_omega_z, -0.03 , 0.35, 0.03, -0.35)
Luminaire_friction_torque connects horizontal_arm with luminaire
+1.0*STEP(.surigcallightingsystem.luminaire_joint_omega_z, -0.01 , 3.8 , 0.01, -3.8) +1.0*STEP(.surigcallightingsystem.luminaire_joint_omega_z, -0.03 , -0.3 , 0.03, 0.3)

Appendix I - MSC Adams authentication report: topology SLS model

The simulation model of the SLS contains six rigid body parts (excluding the ground part):

Part ground Is connected to:	
Flange_tube via flange_tube_joint_fixed_arm	(Fixed Joint)
Part Flange_tube Is connected to:	
Ground via flange_tube_joint_fixed_arm	(Fixed Joint)
Horizontal_swivel_arm via horizontal_swivel_arm_joint	(Revolute Joint)
Horizontal_swivel_arm via horizontal_swivel_arm_applied_torque	(Single_Component_Force)
Horizontal_swivel_arm via horizontal_swivel_arm_friction_torque	(Single_Component_Force)
Part vertical_tube Is connected to:	
Horizontal_swivel_arm via vertical_tube_joint	(Revolute Joint)
Hydraulic_arm via hydraulic_arm_joint	(Revolute Joint)
Horizontal_swivel_arm via vertical_tube_friction_torque	(Single_Component_Force)
Horizontal_swivel_arm via vertical_tube_applied_torque	(Single_Component_Force)
Hydraulic_arm via hydraulic_arm_friction_torque	(Single_Component_Force)
Hydraulic_arm via hydraulic_arm_applied_torque	(Single_Component_Force)
Part horizontal_swivel_arm Is connected to:	
Vertical_tube via vertical_tube_joint	(Revolute Joint)
Vertical_tube via vertical_tube_friction_torque	(Single_Component_Force)
Flange_tube via horizontal_swivel_arm_joint	(Revolute Joint)
Flange_tube via horizontal_swivel_arm_friction_torque	(Single_Component_Force)
Flange_tube via horizontal_swivel_arm_applied_torque	(Single_Component_Force)
Vertical_tube via vertical_tube_applied_torque	(Single_Component_Force)
Part hydraulic_arm Is connected to:	
Vertical_tube via hydraulic_arm_joint	(Revolute Joint)
Horizontal_arm via horizontal_arm_joint	(Revolute Joint)
Horizontal_arm via horizontal_arm_applied_torque	(Single_Component_Force)
Horizontal_arm via horizontal_arm_friction	(Single_Component_Force)
Vertical_tube via hydraulic_arm_applied_torque	(Single_Component_Force)
Vertical_tube via hydraulic_arm_friction_torque	(Single_Component_Force)
Part horizontal_arm Is connected to:	
Luminaire via luminaire_joint	(Revolute Joint)
Luminaire via luminaire_applied_torque	(Single_Component_Force)
Luminaire via luminaire_friction_torque	(Single_Component_Force)
Hydraulic_arm via horizontal_arm_joint	(Revolute Joint)
Hydraulic_arm via horizontal_arm_applied_torque	(Single_Component_Force)
Hydraulic_arm via horizontal_arm_friction	(Single_Component_Force)
Part luminaire Is connected to:	
Horizontal_arm via luminaire_joint	(Revolute Joint)
Horizontal_arm via luminaire_friction_torque	(Single_Component_Force)
Horizontal_arm via luminaire_applied_torque	(Single_Component_Force)

Appendix J - MSC Adams authentication report: verification model kinematics

The SLS Model was verified successfully, based on the MSC Adams report below:

5 Gruebler Count (approximate degrees of freedom)
6 Moving Parts (not including ground)
5 Revolute Joints
1 Fixed Joints
5 Degrees of Freedom for .surgicallightingsystem
There are no redundant constraint equations.

Appendix K - Matlab programming code for data visualization

The code was written to allow data visualization of the simulation runs to obtain the mapping of the required force to reposition the luminaire along a translational axis.

```
close all
clc
clear

%%%%%%%%%%%% Import Excel data
X_x = xlsread('X_vectors_X_trans.xlsx');
Z_x = xlsread('Z_vectors_X_trans.xlsx');
Fx_x = xlsread('Fx_X_trans.xlsx');
Fz_x = xlsread('Fz_X_trans.xlsx');
X_z = xlsread('X_vectors_Z_trans.xlsx');
Z_z = xlsread('Z_vectors_Z_trans.xlsx');
Fx_z = xlsread('Fx_Z_trans.xlsx');
Fz_z = xlsread('Fz_Z_trans.xlsx');

%%%%%%%%% save imported data
save ('data_x', 'Fx_x', 'Fz_x', 'X_x', 'Z_x')
save ('data_z', 'Fx_z', 'Fz_z', 'X_z', 'Z_z')
%load imported data
% load data_x
% load data_z

X_x(:,end)= nan; % cut off last row
Z_x(:,end)= nan;
Fx_x(:,end)= nan;
Fz_x(:,end)= nan;
X_z(:,end)= nan; % cut off last row
Z_z(:,end)= nan;
Fx_z(:,end)= nan;
Fz_z(:,end)= nan;

X_x(X_x==0)=nan; % zeros replaced by NaN to plot correctly
Z_x(Z_x==0)=nan;
Fx_x(Fx_x==0)=nan;
Fz_x(Fz_x==0)=nan;
X_z(X_z==0)=nan;
Z_z(Z_z==0)=nan;
Fx_z(Fx_z==0)=nan;
Fz_z(Fz_z==0)=nan;

% % cutoff= 2;
X_x(1:cutoff,:)= nan; % cut off start behaviour
Z_x(1:cutoff,:)= nan;
Fx_x(1:cutoff,:)= nan;
Fx_x(1:cutoff,:)= nan;
X_z(1:cutoff,:)= nan; % cut off start behaviour
Z_z(1:cutoff,:)= nan;
Fx_z(1:cutoff,:)= nan;
Fz_z(1:cutoff,:)= nan;
X_x = X_x+0.25; % centre luminaire in x-axis
X_z = X_z+0.25 % centre luminaire in z-axis
save ('data_x_rev', 'Fx_x', 'Fz_x', 'X_x', 'Z_x')
save ('data_z_rev', 'Fx_z', 'Fz_z', 'X_z', 'Z_z')
%% load data_x_rev
%% load data_z_rev
```

```
%% Calculate Ft
Ft_x = sqrt((Fx_x).^2+(Fz_x).^2);
Ft_z = sqrt((Fx_z).^2+(Fz_z).^2);
save ('data_x_Ft_x', 'Ft_x', 'Fz_x', 'X_x', 'Z_x')
save ('data_z_Ft_z', 'Ft_z', 'Fz_z', 'X_z', 'Z_z')
% load data_x_Ft_x
% load data_z_Ft_z

% Create work field regions
straal_x = sqrt(X_x.^2+X_z.^2);
straal_z = sqrt(Z_x.^2+Z_z.^2);
indices_x_1 = find(straal_x<=0.475);
indices_z_1 = find(straal_z<=0.475);
indices_x_2 = find(straal_x>=1.87);
indices_z_2 = find(straal_z>=1.87);
indices_x_3 = find(straal_x<=1.93);
indices_z_3 = find(straal_z<=1.93);

Ft_x_rev_1=Ft_x;
Ft_z_rev_1=Ft_z;
Ft_x_rev_2=Ft_x;
Ft_z_rev_2=Ft_z;
Ft_x_rev_3=Ft_x;
Ft_z_rev_3=Ft_z;
% Ft_x_rev_1(indices_x_1)=[NaN];
% Ft_z_rev_1(indices_z_1)=[NaN];
% Ft_x_rev_2(indices_x_2)=[NaN];
% Ft_z_rev_2(indices_z_2)=[NaN];
% Ft_x_rev_3(indices_x_3)=[NaN];
% Ft_z_rev_3(indices_z_3)=[NaN];
x1 = find(isnan(Ft_x_rev_1))';
zl = find(isnan(Ft_z_rev_1))';
x2 = find(isnan(Ft_x_rev_2))';
z2 = find(isnan(Ft_z_rev_2))';
x3 = find(isnan(Ft_x_rev_3))';
z3 = find(isnan(Ft_z_rev_3))';
Ft_x_rev_1(indices_x_1)=0;
Ft_z_rev_1(indices_z_1)=0;
Ft_x_rev_2(x2)=0;
Ft_z_rev_2(z2)=0;
Ft_x_rev_3(x3)=0;
Ft_z_rev_3(z3)=0;
Ft_x_1_clean=-Ft_x_rev_1+Ft_x;
Ft_z_1_clean=-Ft_z_rev_1+Ft_z;
Ft_x_2_clean=-Ft_x_rev_2+Ft_x;
Ft_z_2_clean=-Ft_z_rev_2+Ft_z;
Ft_x_3_clean=-Ft_x_rev_3+Ft_x;
Ft_z_3_clean=-Ft_z_rev_3+Ft_z;
Ft_x_1_clean(Ft_x_1_clean==0)=NaN;
Ft_x_1_clean(Ft_z_1_clean==0)=NaN;
Ft_x_2_clean(Ft_x_2_clean==0)=NaN;
Ft_x_2_clean(Ft_z_2_clean==0)=NaN;
Ft_z_3_clean(Ft_x_3_clean==0)=NaN;
Ft_z_3_clean(Ft_z_3_clean==0)=NaN;

X_x_rev(indices_x)=[NaN];
Z_x_rev(indices_z)=[NaN];

%%% MESH X-DIRECTION
A = 500; % caxis waarde --> caxis([cmin cmax])
B = 500; % ZLim waarde
BX = 2.2;
```

```
BY = 2.2;

% figure(1)
% subplot(1,2,1); mesh(X_x,Z_x,Ft_x);
% subplot(1,2,1); mesh(X_x,Z_x,Ft_x_rev);
subplot(1,2,1); mesh(X_x,Z_x,Ft_x_1_clean);
set(gca,'FontSize',13)
caxis([-A A]);
xlabel('x-value')
ylabel('z-value')
% axis equal
XLim([-BX BX]);
YLim([-BY BY]);
view(2) % top view
title('Plot of 2D topview of Ft during x-axis translation in total work field')
set(gca,'FontSize',13)
% subplot(1,2,2);mesh(X_x,Z_x,Ft_x);
% subplot(1,2,2);mesh(X_x,Z_x,Ft_x_rev);
subplot(1,2,2);mesh(X_x,Z_x,Ft_x_1_clean);
set(gca,'FontSize',13)
caxis([-A A]);
XLim([-BX BX]);
YLim([-BY BY]);
ZLim([-B B]);
xlabel('x-value')
ylabel('z-value')
zlabel('Fx')
colorbar
title('Plot of 3D view of Ft during x-axis translation in total work field')

figure(2)
% subplot(1,2,1); mesh(X_x,Z_x,Ft_x);
% subplot(1,2,1); mesh(X_x,Z_x,Ft_x_rev);
subplot(1,2,1); mesh(X_x,Z_x,Ft_x_2_clean);
set(gca,'FontSize',13)
caxis([-A A]);
xlabel('x-value')
ylabel('z-value')
% axis equal
XLim([-BX BX]);
YLim([-BY BY]);
view(2) % top view
title('Plot of 2D topview of Ft during x-axis translation in total work field')
set(gca,'FontSize',13)
% subplot(1,2,2);mesh(X_x,Z_x,Ft_x);
% subplot(1,2,2);mesh(X_x,Z_x,Ft_x_rev);
subplot(1,2,2);mesh(X_x,Z_x,Ft_x_2_clean);
set(gca,'FontSize',13)
caxis([-A A]);
XLim([-BX BX]);
YLim([-BY BY]);
ZLim([-B B]);
xlabel('x-value')
ylabel('z-value')
zlabel('Fx')
colorbar
title('Plot of 3D view of Ft during x-axis translation in total work field')

figure(3)
% subplot(1,2,1); mesh(X_x,Z_x,Ft_x);
% subplot(1,2,1); mesh(X_x,Z_x,Ft_x_rev);
subplot(1,2,1); mesh(X_x,Z_x,Ft_x_3_clean);
```

```
set(gca,'FontSize',13)
caxis([-A A]);
xlabel('x-value')
ylabel('z-value')
% axis equal
XLim([-BX BX]);
YLim([-BY BY]);
view(2) % top view
title('Plot of 2D topview of Ft during x-axis translation in total work field')
set(gca,'FontSize',13)
% subplot(1,2,2);mesh(X_x,Z_x,Ft_x);
% subplot(1,2,2);mesh(X_x,Z_x,Ft_x_rev);
subplot(1,2,2);mesh(X_x,Z_x,Ft_x_3_clean);
set(gca,'FontSize',13)
caxis([-A A]);
XLim([-BX BX]);
YLim([-BY BY]);
ZLim([-B B]);
xlabel('x-value')
ylabel('z-value')
zlabel('Fx')
colorbar
title('Plot of 3D view of Ft during x-axis translation in total work field')


% %%% MESH Z-DIRECTION
%
% subplot(1,2,1); mesh(X_z,Z_z,Ft_z)
% set(gca,'FontSize',13)
% caxis([-A A]);
% xlabel('x-value')
% ylabel('z-value')
% % axis equal
% XLim([-BX BX]);
% YLim([-BY BY]);
% view(2) % top view
% title('Plot of 2D view of Ft during z-axis translation in total work field')
% subplot(1,2,2); mesh(X_z,Z_z,Ft_z)
% set(gca,'FontSize',13)
% caxis([-A A]);
% XLim([-BX BX]);
% YLim([-BY BY]);
% ZLim([-B B]);
% xlabel('x-value')
% ylabel('z-value')
% zlabel('Fx')
% colorbar
% title('Plot of 3D view of Ft during z-axis translation in total work field')
```

Segment data analysis x translation

```
close all
clc
clear

load data_x_sens_rev
load data_x_sens_model10plus_rev

% r=[0 0.475 1.90 1.93];
straal_x = sqrt(X_x_sens.^2+Z_x_sens.^2);
straal_x1 = straal_x;
straal_x2 = straal_x;
straal_x3 = straal_x;
```

```
straal_x4 = straal_x;
% indices_x_1 = find(straal_x>=0.475);
straal_x1(straal_x1>0.475) = 0;
straal_x1(isnan(straal_x1)) = 0;
straal_x1(straal_x1>0) = 1;

straal_x2(straal_x2>1.7) = 0;
straal_x2(isnan(straal_x2)) = 0;
straal_x2(straal_x2>0) = 1;

straal_x3(straal_x3>=1.9) = 0;
straal_x3(isnan(straal_x3)) = 0;
straal_x3(straal_x3>0) = 1;

Fx_x_sens_model10plus_rev_x1 = Fx_x_sens_model10plus.*straal_x1;

Fx_x_sens_model10plus_rev_x2a = Fx_x_sens_model10plus.*straal_x2;
Fx_x_sens_model10plus_rev_x2 = Fx_x_sens_model10plus_rev_x2a - Fx_x_sens_model10plus_rev_x1;

Fx_x_sens_model10plus_rev_x3a = Fx_x_sens_model10plus.*straal_x3;
Fx_x_sens_model10plus_rev_x3 = Fx_x_sens_model10plus_rev_x3a-Fx_x_sens_model10plus_rev_x2a;

% Ft_x4a = Ft_x.*straal_x4;
Fx_x_sens_model10plus_rev_x4 = Fx_x_sens_model10plus-Fx_x_sens_model10plus_rev_x3a;

Fx_x_sens_model10plus_rev_x1(Fx_x_sens_model10plus_rev_x1==0)=NaN;
Fx_x_sens_model10plus_rev_x2(Fx_x_sens_model10plus_rev_x2==0)=NaN;
Fx_x_sens_model10plus_rev_x3(Fx_x_sens_model10plus_rev_x3==0)=NaN;
Fx_x_sens_model10plus_rev_x4(Fx_x_sens_model10plus_rev_x4==0)=NaN;

%% Values to plot:
Mean1a = nanmean(Fx_x_sens_model10plus_rev_x1);
Mean1 = nanmean(Mean1a)
Std1a = nanstd(Fx_x_sens_model10plus_rev_x1);
Std1 = nanstd(Std1a)
Max1a = nanmax(Fx_x_sens_model10plus_rev_x1);
Max1 = nanmax(Max1a)
Mean2a = nanmean(Fx_x_sens_model10plus_rev_x2);
Mean2 = nanmean(Mean2a)
Std2a = nanstd(Fx_x_sens_model10plus_rev_x2);
Std2 = nanstd(Std2a)
Max2a = nanmax(Fx_x_sens_model10plus_rev_x2);
Max2 = nanmax(Max2a)
Mean3a = nanmean(Fx_x_sens_model10plus_rev_x3);
Mean3 = nanmean(Mean3a)
Std3a = nanstd(Fx_x_sens_model10plus_rev_x3);
Std3 = nanstd(Std3a)
Max3a = nanmax(Fx_x_sens_model10plus_rev_x3);
Max3 = nanmax(Max3a)
```

Segment data analysis z translation

```
close all
clc
clear

% % load data_x_rev
% % load data_z_rev

%% Calculate Ft
% % Ft_x = sqrt((Fx_x).^2+(Fx_x).^2);
% % Ft_z = sqrt((Fx_z).^2+(Fz_z).^2);
% % save ('data_x_Ft_x', 'Ft_x', 'Fz_x', 'X_x', 'Z_x')
```

```
% % save ('data_z_Ft_z', 'Ft_z', 'Fz_z', 'X_z', 'Z_z')
load data_x_Ft_x
load data_z_Ft_z

% r=[0 0.475 1.90 1.93];
straal_x = sqrt(Z_x.^2+Z_z.^2);
straal_x1 = straal_x;
straal_x2 = straal_x;
straal_x3 = straal_x;
straal_x4 = straal_x;
% indices_x_1 = find(straal_x>=0.475);
straal_x1(straal_x1>0.475) = 0;
straal_x1(isnan(straal_x1)) = 0;
straal_x1(straal_x1>0) = 1;
straal_x2(straal_x2>1.7) = 0;
straal_x2(isnan(straal_x2)) = 0;
straal_x2(straal_x2>0) = 1;
straal_x3(straal_x3>=1.9) = 0;
straal_x3(isnan(straal_x3)) = 0;
straal_x3(straal_x3>0) = 1;

Ft_x1 = Ft_x.*straal_x1;
Ft_x2a = Ft_x.*straal_x2;
Ft_x2 = Ft_x2a - Ft_x1;
Ft_x3a = Ft_x.*straal_x3;
Ft_x3 = Ft_x3a-Ft_x2a;
% Ft_x4a = Ft_x.*straal_x4;
Ft_x4 = Ft_x-Ft_x3a;

Ft_x1(Ft_x1==0)=NaN;
Ft_x2(Ft_x2==0)=NaN;
Ft_x3(Ft_x3==0)=NaN;
Ft_x4(Ft_x4==0)=NaN;
% figure(1),plot3(X_x,X_z,Ft_x1)
% figure(2),plot3(X_x,X_z,Ft_x2)
% figure(3),plot3(X_x,X_z,Ft_x3)
% figure(4),plot3(X_x,X_z,Ft_x4)
figure(1),mesh(X_x,X_z,Ft_x1)
figure(2),mesh(X_x,X_z,Ft_x2)
figure(3),mesh(X_x,X_z,Ft_x3)
figure(4),mesh(X_x,X_z,Ft_x4)

%% Values to plot:
Mean1a = nanmean(Ft_x1);
Mean1 = nanmean(Mean1a)
Std1a = nanstd(Ft_x1);
Std1 = nanstd(Std1a)
Max1a = nanmax(Ft_x1);
Max1 = nanmax(Max1a)
Mean2a = nanmean(Ft_x2);
Mean2 = nanmean(Mean2a)
Std2a = nanstd(Ft_x2);
Std2 = nanstd(Std2a)
Max2a = nanmax(Ft_x2);
Max2 = nanmax(Max2a)
Mean3a = nanmean(Ft_x3);
Mean3 = nanmean(Mean3a)
Std3a = nanstd(Ft_x3);
Std3 = nanstd(Std3a)
Max3a = nanmax(Ft_x3);
Max3 = nanmax(Max3a)
```

Appendix L - Maps of required force at luminaire location

Maps of the required force at various location of the luminaire in the SLS work field. The vertical colour bar on the right indicates the force value scale of the map in the range of 500 until -500 Newton.

Figure 73 - Required forces in x-direction (Fx) for luminaire reposition along x-axis in total SLS work field.

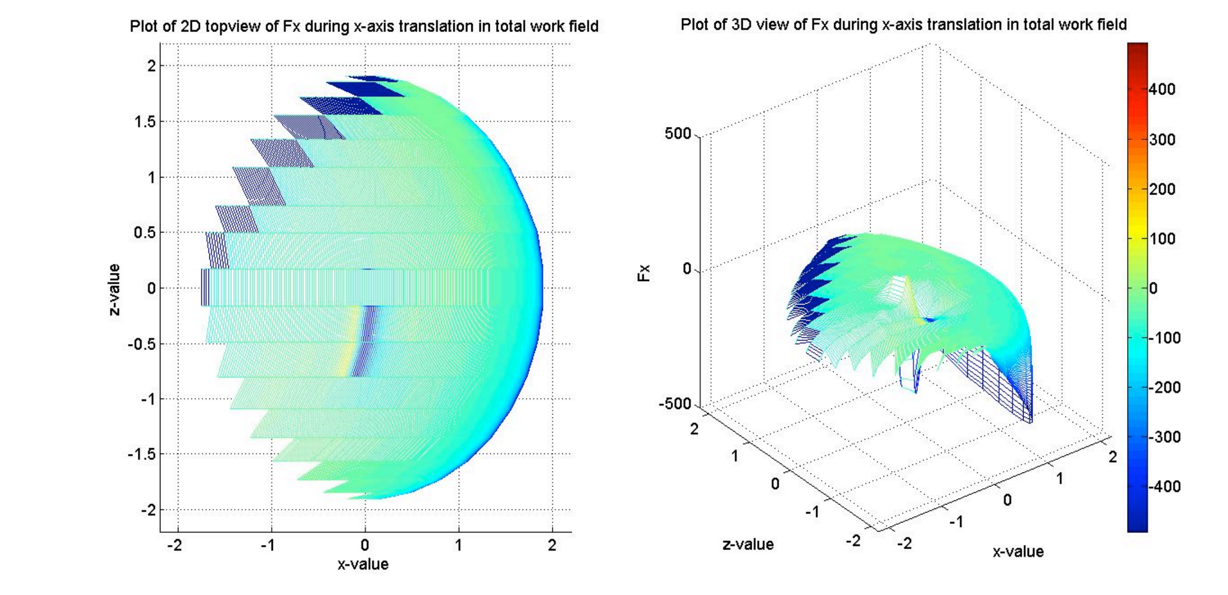


Figure 74 - Required forces in z-direction (Fz) for luminaire reposition along x-axis in total SLS work field.

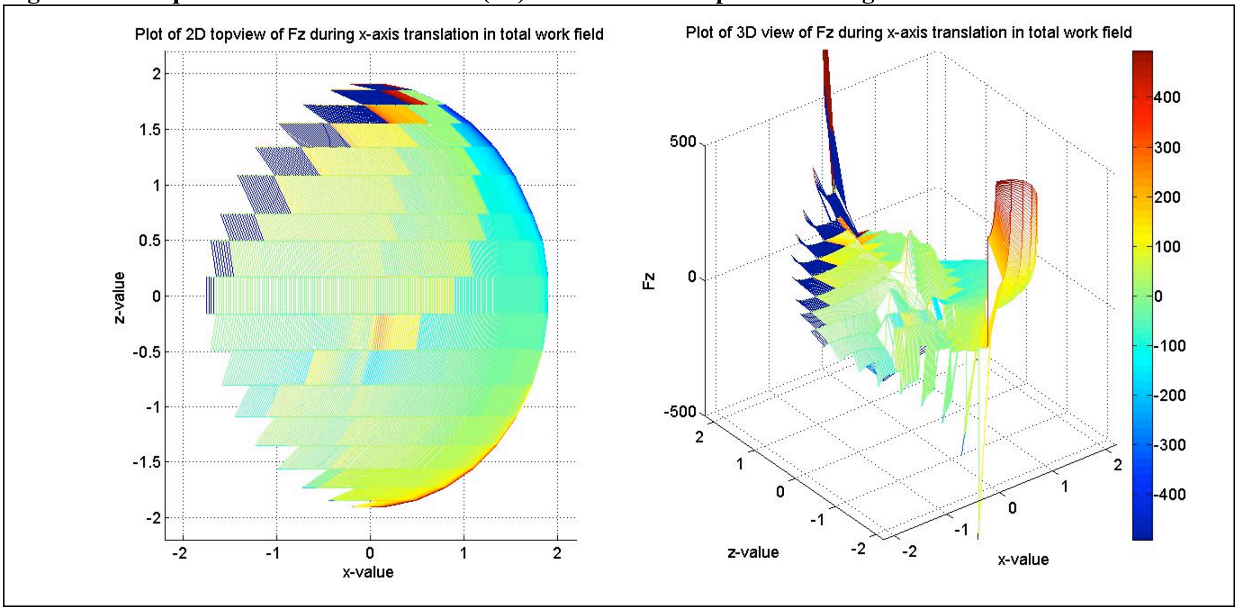


Figure 75 - Required forces in x-direction (Fx) for luminaire reposition along z-axis in total SLS work field.

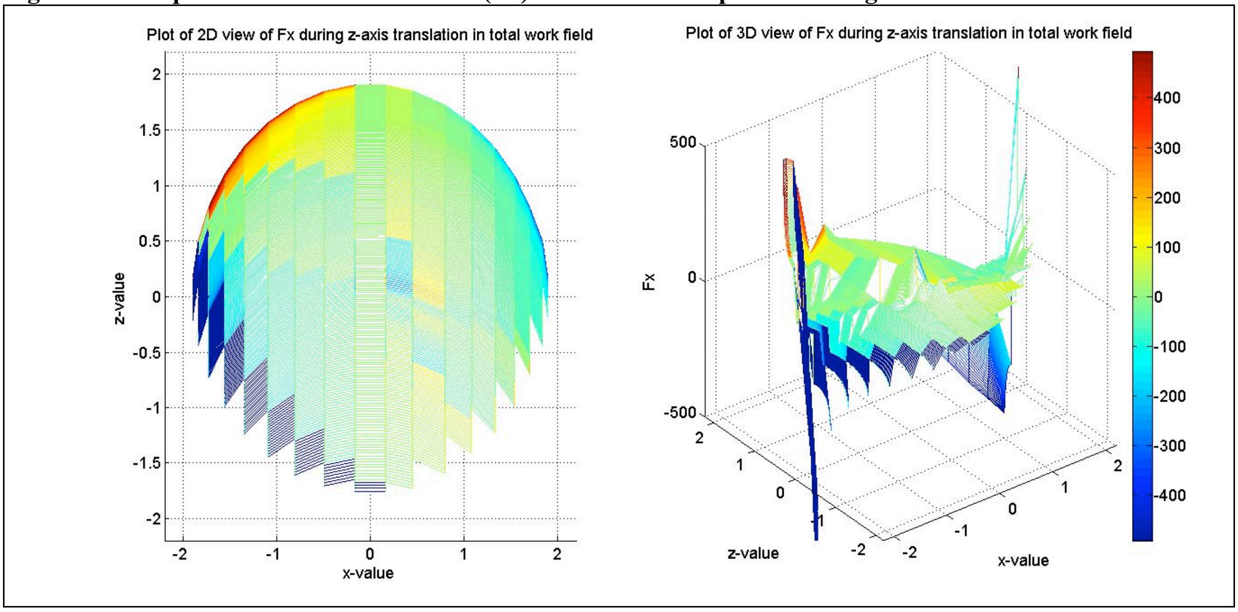


Figure 76 - Required forces in z-direction (Fz) for luminaire reposition along z-axis in total SLS work field.

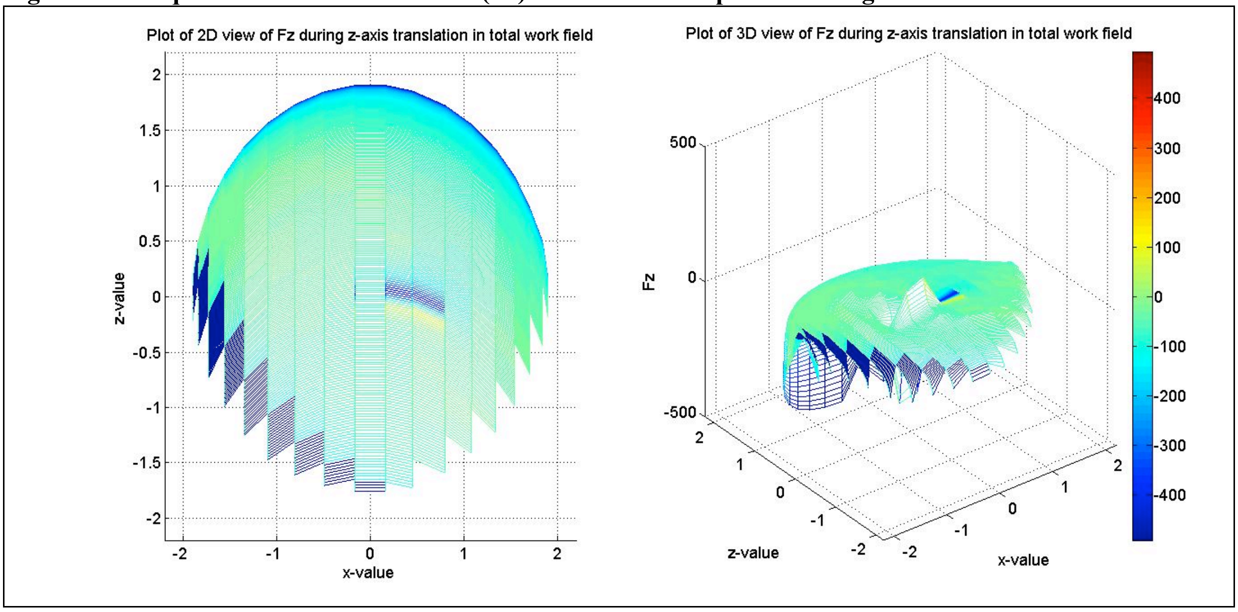


Figure 77 - Required forces in x-direction (Fx) for luminaire reposition along x-axis in central SLS work field.

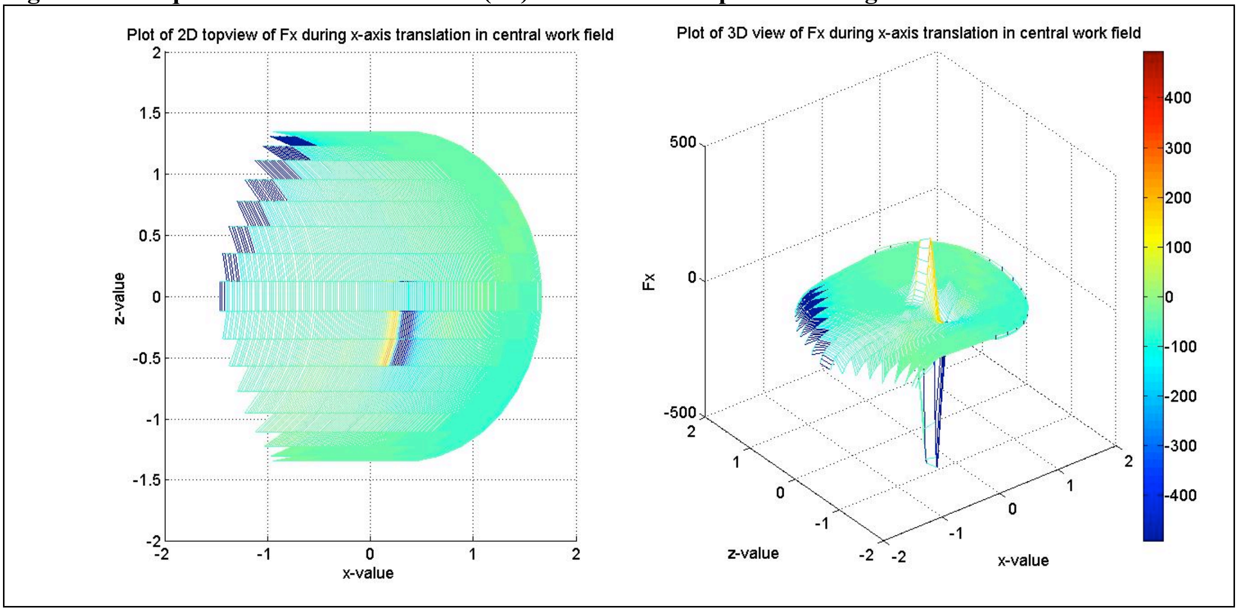


Figure 78 - Required forces in z-direction (Fz) for luminaire reposition along x-axis in central SLS work field.

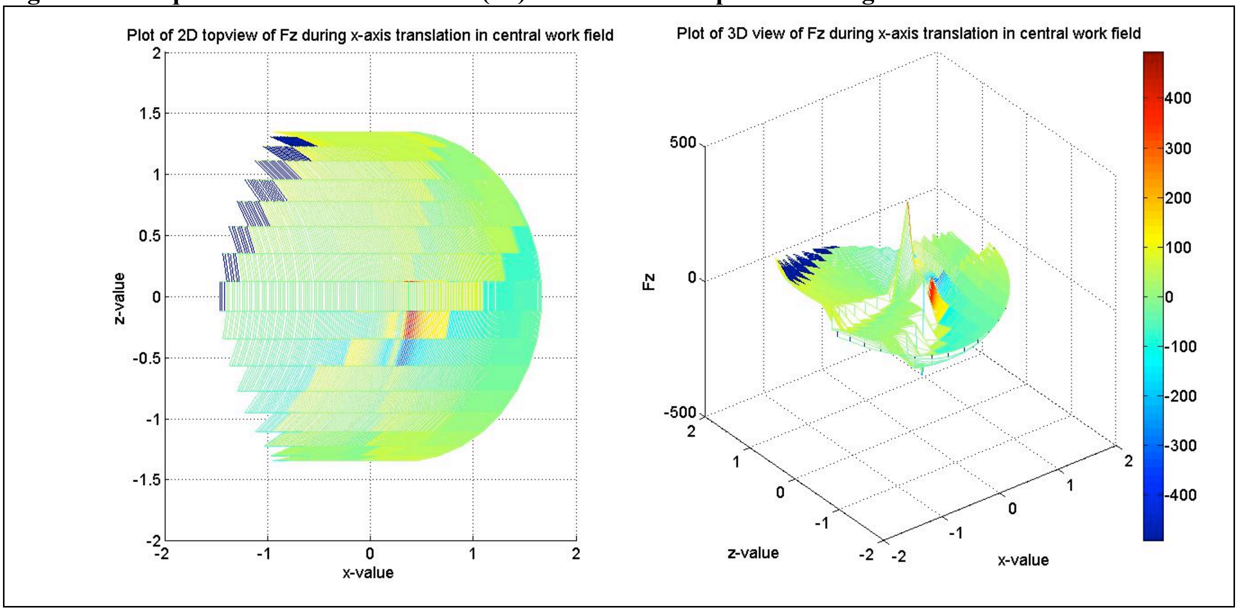


Figure 79 - Required forces in x-direction (Fx) for luminaire reposition along z-axis in central SLS work field.

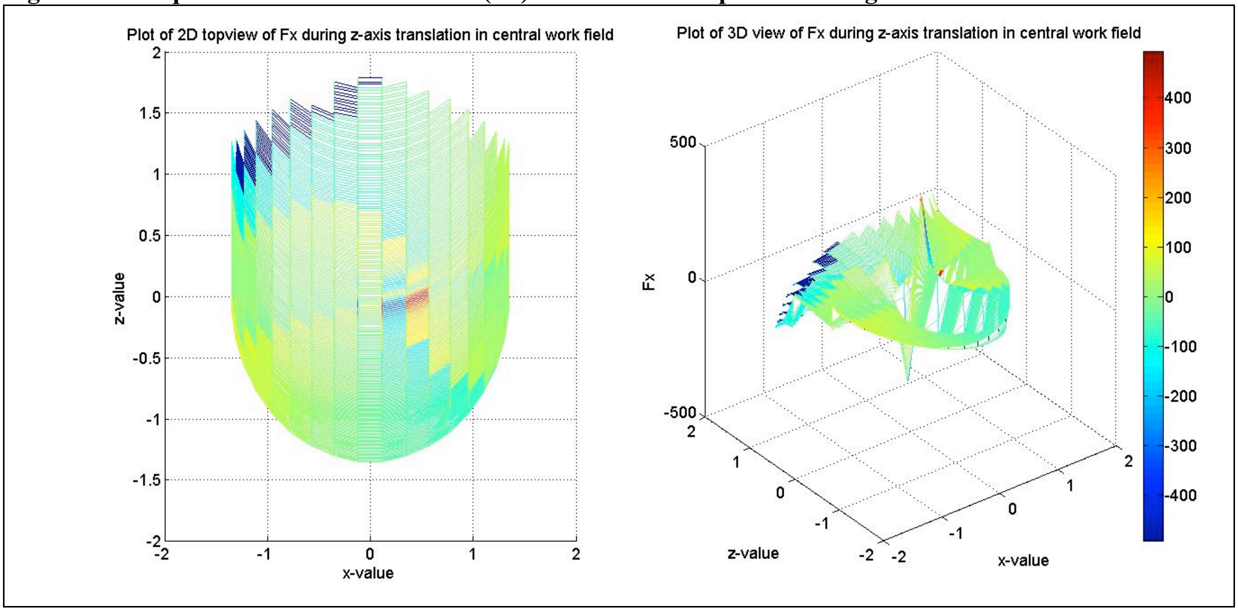
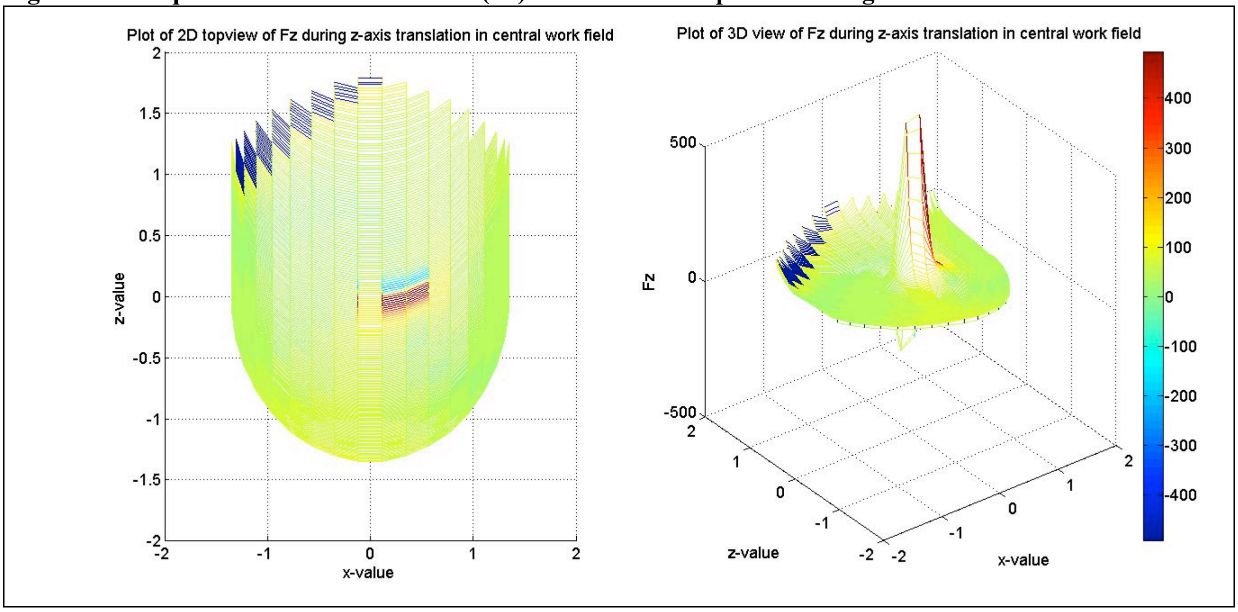


Figure 80 - Required forces in z-direction (Fz) for luminaire reposition along z-axis in central SLS work field.



Appendix M - Additional figures of the SLS sensitivity analysis

The comparison of the force output of the SLS model with normal mass distribution values versus a models with plus and minus 10% of luminaire. It shows that changes in force output order of magnitude were primarily due to the inertia of the luminaire.

Figure 81 - SLS sensitivity analysis: normal versus +10% mass of the luminaire

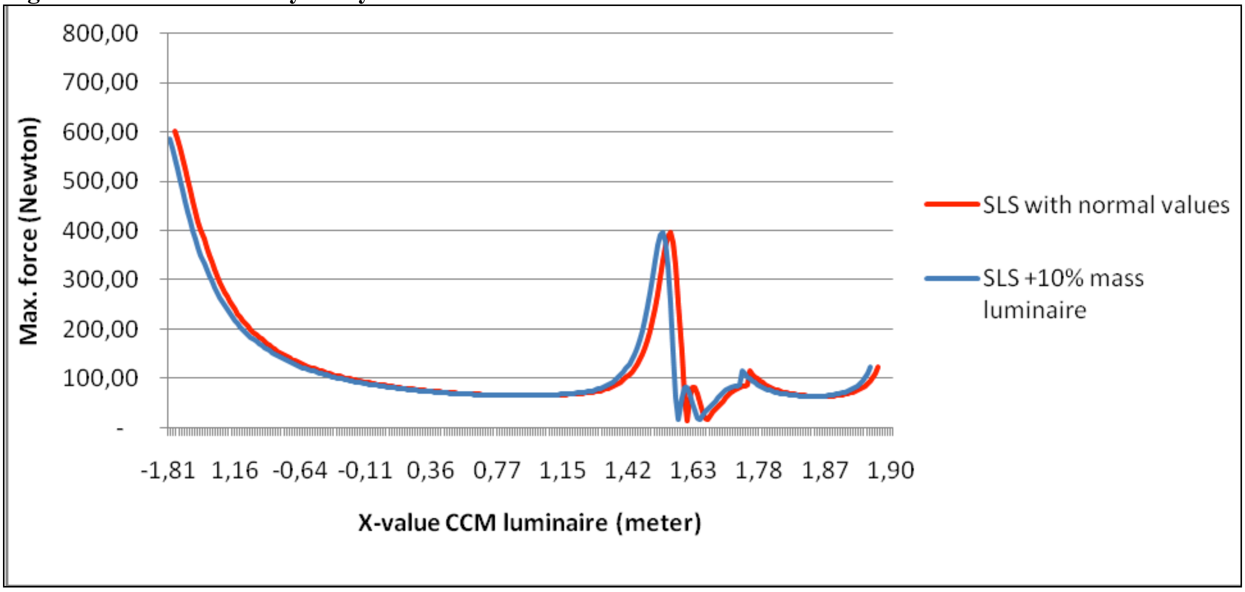
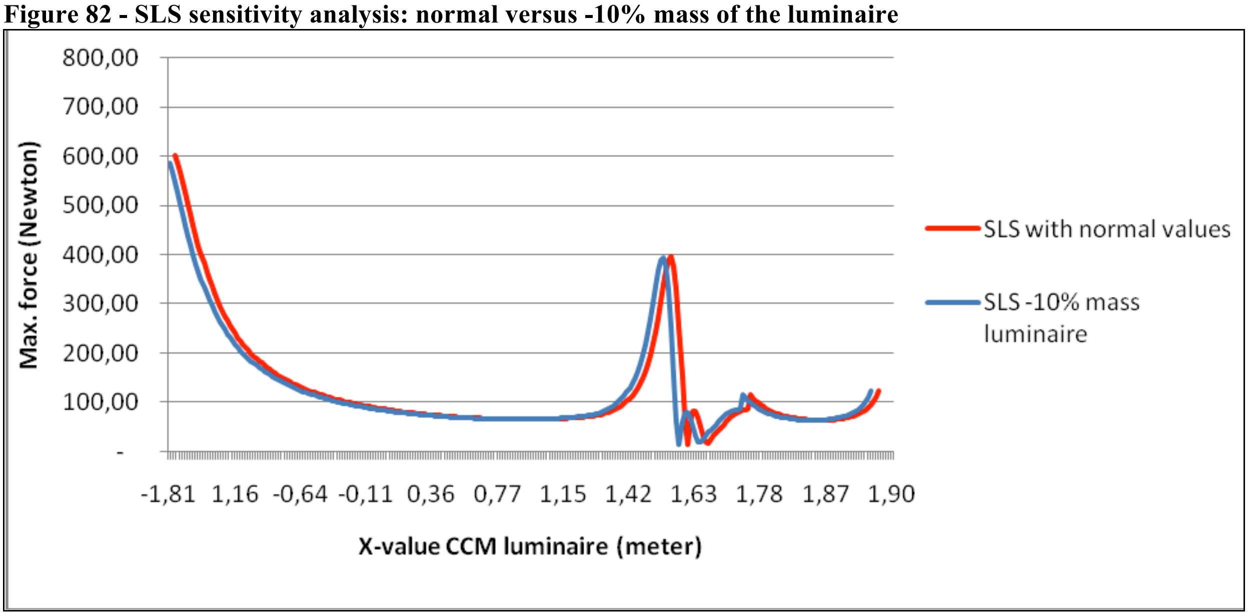


Figure 82 - SLS sensitivity analysis: normal versus -10% mass of the luminaire



List of figures & tables with page numbers

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PART C