Structural Study of a Robotic System for Sils Surgery

Doina Pisla[1] , Nicolae Crisan[2] , Ionut Ulinici[1] , Bogdan Gherman[1] ,
Corina Radu[2] , Paul Tucan[1] , and Calin Vaida[1(✉)]

[1] CESTER, Technical University of Cluj-Napoca, 400114 Cluj-Napoca, Romania
calin.vaida@mep.utcluj.ro
[2] "Iuliu Hatieganu" University of Medicine and Pharmacy, 400347 Cluj-Napoca, Romania

**Abstract.** The use of smart robot technologies is slowly eliminating the limitations of manual single incision laparoscopic surgery (SILS). In this paper, the authors present a parallel robotic structure designed for use in SILS surgery, the mechanical structure of the robotic device is presented and its motion capabilities relative to the surgical task. Furthermore, a FEM analysis of the components of the robotic structure that are most subjected to strain during operation was carried out, as to study the components capability of maintaining the structural integrity of the robotic system without being subjected to deformations that could impede the functioning of the robotic device.

Keywords: Robotic SILS · Parallel Robot · FEM

1 Introduction

Single incision laparoscopic surgery (SILS) is a further evolution of minimally invasive surgery (MIS) and differs from it by requiring a single incision into the patient's body through which the instrumentation for the surgical procedure is inserted. Though the procedure presents clear advantages [1] there are several complexities entailed by the procedure's characteristics, mainly difficulty in instrument manipulation and increased chance of collision between instruments and between instruments and the laparoscope/laparoscopic camera, considering the increased proximity of the instruments as all together with the camera are introduced and manipulated within the limitations of a singular incision. For this purpose, specialized instrumentation such as curved and flexible instruments have been developed for use in manual surgery. Furthermore, to increase the ease of the procedure and taking into account its risk, robotic systems have been implemented. These have been shown to reduce risks associated with SILS and the capacity to bypass instrument manipulation difficulties.

1.1 State of the Art in Robotic SILS

Robotic systems dedicated for use in single incision laparoscopic surgery can be classified based on end-effector configuration, in that regard there are:

1. **Systems with a single hyper-flexible end-effector for the instruments and camera**: Of these there is the da Vinci SP robotic system [2, 3].The instruments and cameras are contained within a tubular structure that is inserted through the incision, and such a construction removes the need for a conventional SILS port. The flexible instruments and laparoscopic camera of the SP system offer increased visibility and high dexterity when compared to classical SILS instruments though this comes at the cost of a reduced manipulation force for tissue handling, due to the structure of the instruments that presents multiple bends.

2. **Multi-arm independent robotic structures each arm guiding a single instrument:** Of these there is the Senhance robotic system [4, 5] which has three independent serial robotic arms, one for each instrument and another for the laparoscopic camera. This robotic device maintains the need for a conventional SILS port for the procedure, and while the triple-arm structure implies greater motion outside the surgical space, its configuration allows for increased forces and stability at the level of the end effector.

3. **Multi-arm robotic structures positioned on a single central platform/column:** Of these there is the SPORT robotic system [6, 7] which contains two articulated arms and two lighted cameras placed on a platform attached to an actuated column Other devices are also being developed for minimally invasive procedures and are the subject of research dedicated towards ensuring efficient surgical procedures with patient safety and ease of use in mind [8-13].

Following the introduction, Sect. 2 describes the inclusion of a robotic system into a SILS surgical procedure and details how the proposed robotic device can mechanically achieve the tasks pertaining to each step of the surgical procedure. Section 3 presents the robot assembly, and its mechanical subassemblies are studied detailing the role of each component in executing the motions at the level of the end-effector followed by Sect. 4 where FEM analyses of the more strained components in scenarios of interest are presented. In Sect. 5 the final ideas about the paper are presented.

2   Parallel Robotic System for SILS

2.1   Robotic Integration in Medical Procedure

The SILS robotic system proposed in this paper [13, 14] must be assimilated in the medical protocol pertaining to the respective procedure. In (Fig. 1.), where the steps of the medical procedure encompassing the medical (non-robotic tasks) and technical (robot related tasks) for each step are presented [15]. The medical procedure is divided into 6 separate steps. The first step "preplanning" has the purpose of ensuring that the parameters for the medical procedure and the integration of the robotic system are well defined. The second step "preparation" deals with preparing the patient and operative space for the procedure and readying the robotic device for the surgical task. This is followed by the "insertion" step in which the robotic device is used to introduce the instruments and camera within the operative space. The fourth step "positioning & orientation" ensures that the robotic system is prepared for safe and efficient instrument manipulation. The fifth step "Surgical task" refers to instrument manipulation while

finalization aims to lead to the patient's safe removal from the surgery room and returning the robotic system to its initial state.

STEP	Medical considerents	Robot Considerents
Preplanning	+Patient file study +Definition of therapeutical approach	+Patient positioning study +Remote center of motion definition (RCM)
Preparation	+Patient positioning on table +Creation of SILS incision +CO_2 insuflation of abdominal cavity	+Instruments and camera mounting +Testing of functionality +Robot placement in home position
Insertion	+Patient state monitoring	+Instrument & camera positioning above RCM +Insertion of instruments & camera in abdominal cavity
Positioning & orientation	+Patient state monitoring	+Platform positioning around entry point +Locking platform into place
Surgical task	+Patient state monitoring	+Manipulation of surgical instruments by surgeon to fulfill surgical task
Finalization	+CO_2 removal from abdomen +SILS port removal +Closing the incision	+Removal of instruments & camera from abdomen +Returning platform to point above RCM +Returning platform to home position +Removal of instruments & camera from robot

Fig. 1. Medical procedure with robot integration

2.2   The SILS Robot Platform Motions

In Fig. 2. The kinematic scheme used in the mechanism definition is overlayed on the robotic platform. With respect to the medical procedure steps illustrated in Sect. 2.1, the first robot action is represented by the definition of the remote center of motion. This is done taking into account the patients position on the table, the configuration of the SILS port inserted into the incision and the position of the point on the instrument platform (which in this stage represents the end-effector) that is used to define the tool center point of the end effector, taking into account the current construction of the platform and the configuration of the instruments and camera on the platform, is represented by the point at the tip of the laparoscopic camera mounted on the platform. That point is aligned with the entry into the incision, and it represents the remote center of motion for the camera and instrument assembly in Fig. 2 it is marked as the entry point and represents the RCM for the procedure. It is to be noted that the instruments themselves have independent RCM-s, which are defined relative to this point.

For the **preparation stage**, the instruments and camera are mounted and their functionality is tested after which the robot is brought into its homing position.The homing position represents a configuration in which the end-effector is placed as far away from the insertion point while also maintaining a orientation of the instrument platform perpendicular to the patient bed.To ensure homing, joints $q5$, $q4$, $q3$, $q1$, and $q2$ are actuated along their respective vertical axes in tandem, to maintain the laparoscope's tip colinear with the entry direction into the abdominal cavity (not moving the joints in tandem and

maintaining set distances between them, in the vertical plane can result in the tilting of the instrument platform).
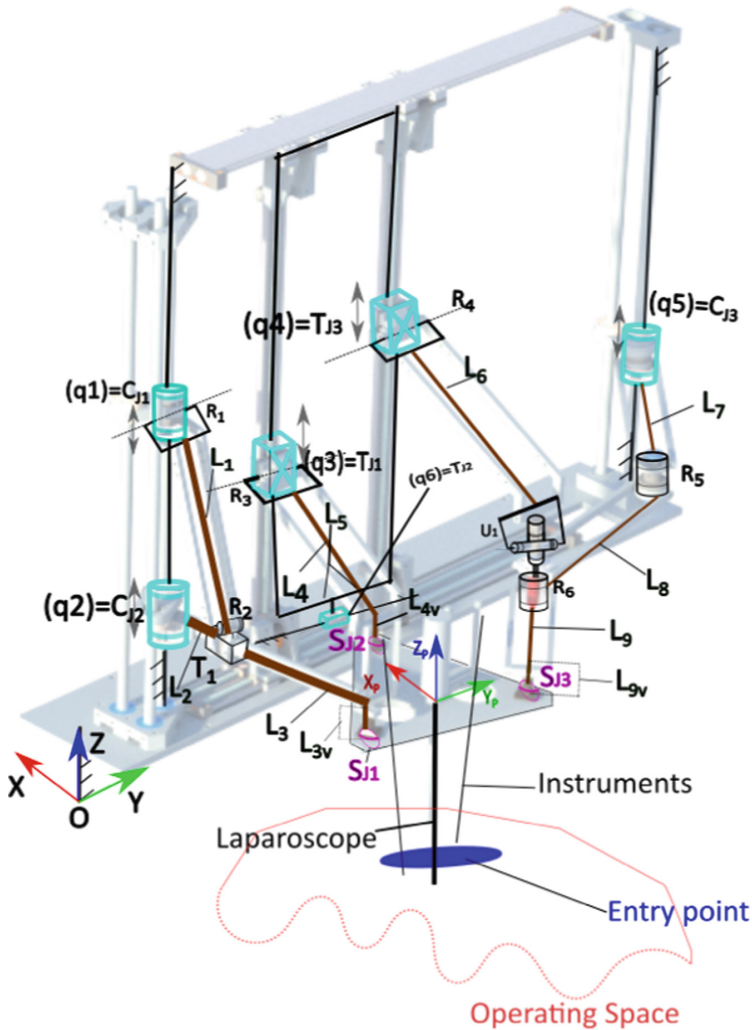

Fig. 2. Kinematic scheme overlaid on robotic platform

For homing it must be ensured that:

- the distance between q1 and q2 on the vertical axis is at 393 mm;
- the distance between q3 and q2 on the vertical axis is set at 158 mm in the positive direction of the Z axis;
- the distance between q4 and q3 is set at 218 mm in the positive direction of the Z axis;

- the distance between q5 and q4 is set at 277 mm in the negative direction of the Z axis.

The q6 joint assembly does not have a set distance at which it must be placed during operation, as it moves though, the previous distances between the other joints must be ensured.

For the **insertion stage** the platform is carried in a point slightly above the RCM. After this, the instrument platform is moved in the negative direction of the Z axis (down), into the abdominal cavity, by actuating joints q1 through q5 in tandem and maintaining q6 at its current position.

For the **positioning and orientation stage** it is to be noted that the incision into the patient's body will not always be parallel to the horizontal plane and as such the tilting of the instrument platform will be necessary. In this eventuality, the set distances between joints q1 through q5 will contain different values relative to the ones defined above (which are for the case in which the incision is parallel to the horizontal plane). It is for this purpose that a 6 DOF configuration for the robot platform is necessary, as it allows the positioning of the platform in the vertical and horizontal planes and its orientation relative to these planes.

After positioning around the entry point the platform's motion is limited by locking q6, while at this point the necessity of compensatory motions of the platform relative to the motion of the instruments in the next stage, requires the q1 through q5 joints to no longer be actuated in tandem, only allowing their independent motion relative to one another.

For the **surgical task**, the motion of the instruments is induced independently by the instrument actuation systems, while the platform only compensates for the orientation of the instruments with very small and precise motions in the order of up to 50 mm displacements of the non-locked joints on their vertical axes.

For the **finalization stage** the reverse of the previous steps must be carried out.

3   The 6 DOF Robotic Platform

The robotic device (Fig. 3.) has a modular parallel structure which was adopted in similar devices [15], comprised of two modules, the robot platform which is comprised from the fixed base/frame, the 6 active joints representing the q1 through q6 in Sect. 2.2, marked in magenta in Fig. 3, their respective guides marked with green and red, a series of passive joints marked with cyan and the robotic arms that link the actuated joints to the mockup instrument platform through three passive spherical joints mounted on the platform (cyan). The robotic device is actuated by 6 motors, each of them actuating one of the joints. The second module is represented by the instrument platform, which contains the mechanisms necessary to actuate the instruments after insertion in the patient's abdomen.

When referring to the robot platform, the instrument platform is the end-effector of the device. The end-effector is actuated through three kinematic chains from here on referred to as motion chains, all of which are connected to the platform through three spherical joints. The motion chains are highlighted with a dotted line in Fig. 3 from left to right in yellow, orange and black.
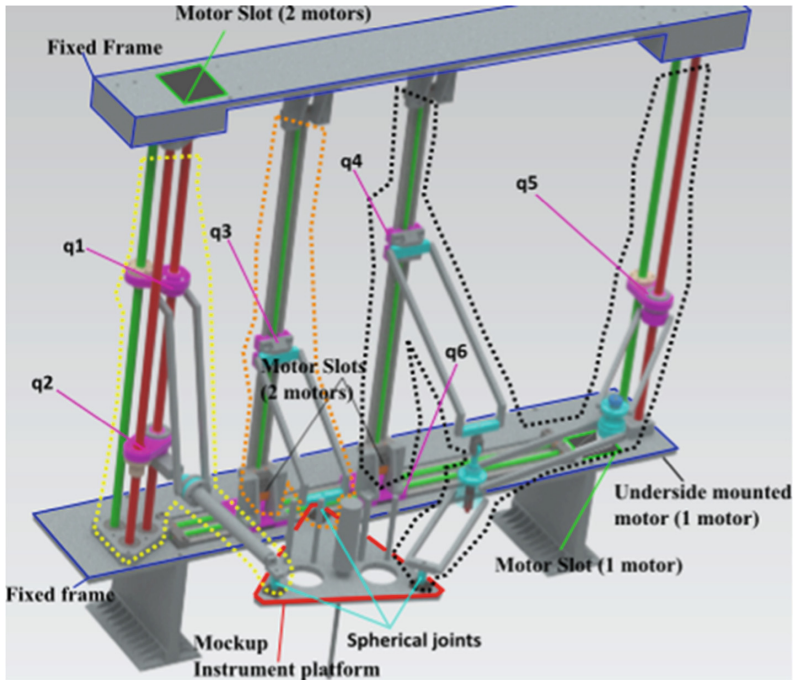
Fig. 3. The parallel SILS robotic system

3.1 The First Motion Chain

The first motion chain (Fig. 4) is comprised of two motors (1) actuating the translation joints with free rotation (7), (9).
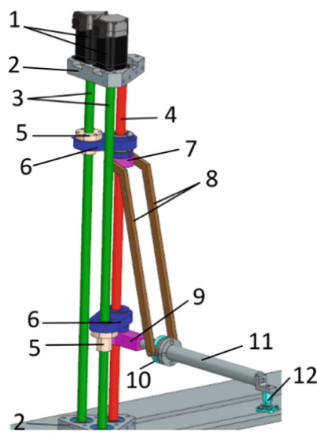

Fig. 4. The first motion chain

The transmission of the motion from the motors is done through a screw(3)-nut(5) mechanism connected to the linear bearing assemblies forming the active joints (7),(9) through a connector comprised of two parallel axial bearings mounted in a aluminum case (6) connecting the nut to the linear bearings. As the linear bearings move along their axis (4), the distance between them can remain either constant, in which case the end of the kinematic chain represented by the passive spherical joint assembly (12) executes a motion in the vertical plane. If the joints move relative to one another, the arms (8) actuate a passive translation joint (10) which is constrained by a piston assembly (11). This motion allows the tilting of the spherical joint, and can induce tilting in the instrument platform, as constrained by the other two motion chains.

3.2   The Second Motion Chain

The second motion chain (Fig. 5.), uses one motor (8') to actuate a linear slider (3') through a screw-nut mechanism (2'), along its vertical axis (1').
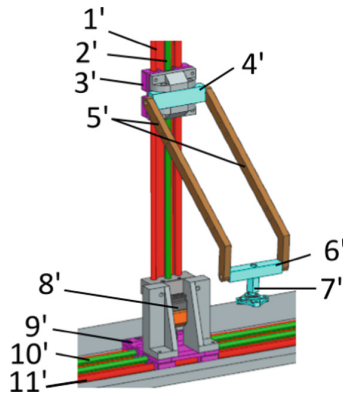

Fig. 5. Second motion chain

This moves the arms (5') along the vertical axis of the assembly, which is constrained to the instrument platform through the spherical joint assembly (7'). In order for the motion to be without stutters, at both ends of the arms, there are two passive rotation joints (4') and (6'). If the other motion chains are not actuated in tandem with this one, the spherical joint assembly and passive rotation joints allow for the forward/backward tilting of the spherical joint and the instrument platform, for sideways tilting, the rail (11') – slider (9') assembly is actuated through the screw (10'), which is a part of the q6 translation joint as presented in Sect. 3.

3.3   The Third Motion Chain

The third motion chain (Fig. 6.), is the amplest of the three, containing two motors for actuation (9") and (15"), being also connected to the q6 joint and directly linked through it to the second motion chain. The motion of the first part of the motion chain

represented by the assembly containing elements (1") through (7") and (9") through (13") is an exact copy of the second motion chain with the difference being that the spherical joint at the end is replaced by an universal joint (7"). This in turn is connected to a passive rotation joint (8"). For the second part of the motion chain, in a similar manner to the first motion chain, the motor 15" transmits motion through the screw (17")-nut (8") mechanism to the linear bearing assembly that comprises the active joint q5 (20") through an aluminum casing (19") with parallel axial bearing connecting the nut to the joint assembly. This motion in turn is transmitted to a passive rotation joint assembly (22") through the arms (21") which also have a free passive rotation at both edges. Through arms (23") rotation joint (22") is connected to rotation joint (8") which represents the common connection between the first part of the motion chain, the second part and the spherical joint (14") connected to the instrument platform, which as in the case of the second motion chain also contains two passive rotation joints at both ends. If motor (9") is actuated in tandem with motor (15") and the other motors from the other motion chains the spherical joint assembly achieves a motion along the vertical axis. If (9") and (15") are actuated separately, tilting motions in both directions can be achieved, provided that the other motion chains are also actuated in order to compensate. Elements (11") through (13") represent the q6 joint.
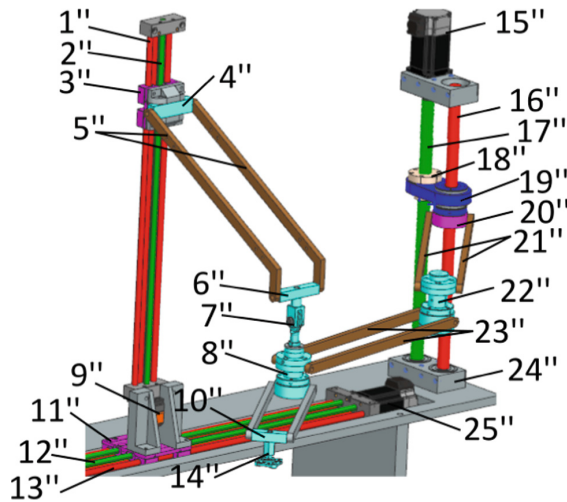

Fig. 6. The third motion chain

It should be noted that due to the particular configuration of the entire robotic system, and all three motion chains being connected through the instrument platform, actuating only a single motion chain while the others are not will only result in needless exertion of the motors, and possible strain on the mechanical structure of the actuated chain, as such the robot cannot work without full actuation of all three motion chains at all times.

4   FEM Analysis of System Components

While the construction of the robotic system ensures negligibly small forces being exerted upon the robot's components, a FEM analysis of what would be the most strained components has been done, to minimize any risks during its interaction with patients [16, 17]. The elements that were studied are represented by the connecting arms between the actuated joints and the instrument platform (highlighted with brown in Sects. 3.1 to 3.3). As these arms take on the total weight of the instrument platform, instruments and laparoscope it was deduced that the arms are the elements that would be most susceptible to mechanical deformations during operation, which could lead to errors during the surgical procedure, as such a FEA was performed to assess their stiffness.

Figure 7. Represents one of the arms connecting q1 to the piston assembly that is in turn connected to the instrument platform through the spherical joint (all part of the first motion chain at 3.1). The conditions considered were that the minimum distance between the q1 and q2 joints has been set, and the second and third kinematic joints are inactive and only hold the platform via mechanical blocking owing to the structure of each chain (no motor breaking included), as such it was calculated that the studied arm would have to undergo pressure equivalent to slightly under $\mathbf{F_1 = 10N}$ perpendicular to the arm's length, at the point of contact between it and the piston assembly. It can be observed that in this case the arm made from aluminum would be subjected to a 0.0836 mm deformation at the tip (a negligible value).
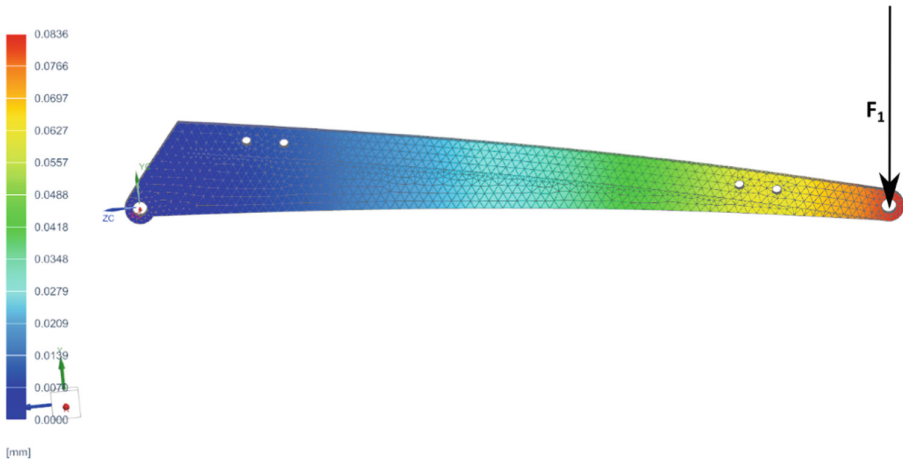

Fig. 7.   The deformations of the q1 arm under the effect of a vertical force

In Figs. 8 and 9 the same situation in which the other kinematic chains were disabled, was studied. This results in a similar force parallel to the arm lengths at the point of contact with the spherical joints. In the case of Fig. 8. The arm is the one connecting the q3 joint to the passive spherical joint on the platform, and it was considered that the weight of the platform dragged the arm and placed it in a as near to vertical position as possible given mechanical limitations, under these conditions the aluminum arm would suffer a

0.0812 mm deformation at the connecting point between it and the spherical joint under the action of a force of $\mathbf{F_i} = \mathbf{10N}$.
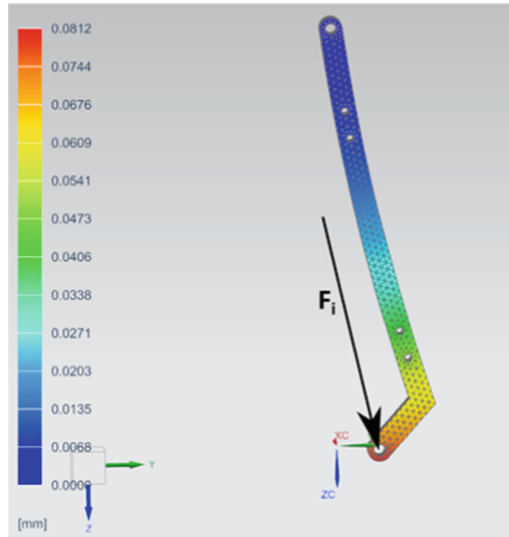

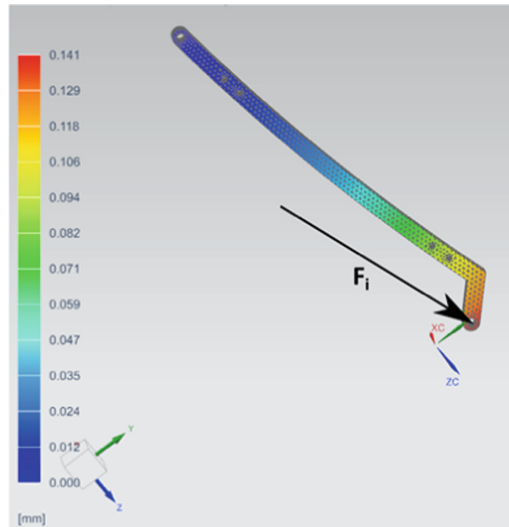**Fig. 8.** The deformations of the q2 arm under the effect of a 10N force

Fig. 9. The deformations of the q4 arm under the effect of a 15N force

In Fig. 9. The arm connecting the q4 joint to the platform was studied, under the same conditions. This arm is connected to a universal joint which links it to an assembly containing 4 passive rotation joints, the passive spherical joint the connecting arms

between these two and the instrument platform, as such, in this case a $\mathbf{F_i = 15N}$ force was considered to exert pressure upon the arm which has been brought in the same position as the arm in 8a. The result is a 0.141 mm deformation at the point of contact. This represents a near twice as large of a deformation compared to the previous arms, though only in a scenario where the rest of the robot joints are completely inactive, and the assembly held by the arm is basically a deadweight.

While the forces studied here are rather small, they are slightly above the estimated weight of the platform and instruments, when divided between each arm. A doubled force would result in deformations over 1mm, which could potentially pose a threat as precision during surgical operation should be under 1mm [18]. Fortunately the platform is expected to remain still once instrument insertion inside the patient's body is done, and as such any additional forces acting upon the arms of the robot cannot occur, therefore it was determined from these FEM simulation that the most strained components of the robotic arm, would not suffer any major deformations under the set conditions, and as such during normal systems operation the robotic arms would most definitely be capable of without any danger.

Additionally, during singular positions when the platform is rotated around its vertical axis most of the concentrated forces would act directly upon the spherical connectors, fortunately to reach those positions all 6 actuators would have to be set for a set of specific values which cannot be reached accidentally.

5   Conclusions

This paper focuses on the mechanical design of a parallel modular robot with 6 degrees of freedom developed for use in SILS surgery. The design of the robotic structure and its subassemblies have proven to be capable of fulfilling the necessary tasks implied by the medical protocol pertaining to a SILS procedure. Each of the three motion chains that make up the robotic structure have shown a rigid structure capable of ensuring the precision and stability of the instrument platform, which are imperative in the safe execution of the robotic surgical tasks. The robotic arms that support the full weight of the instrument platform, instruments and laparoscope have been subjected to a FEM analysis studying the deformations that would occur during an erroneous functioning of the device when these elements would be forced to independently maintain the platform's position and orientation. The deformations observed were negligible enough to support the capacity of the device to maintain the platform stable. The results shown in this paper present the robotic structure as a viable solution for a SILS robotic system and have shown the device's mechanical structure's capability of safely operating the instruments and instrument platform and withstand its weight and forces implied during operation without having any risk to the patient.

References

1. Far, S.S., Miraj, S.: Single-incision laparoscopy surgery: a systematic review. Electron Physician, pp. 3088–3095 (2016)
2. Peters, B.S., Armijo, P.R., Krause, C., Choudhury, S.A., Oleynikov, D.: Review of emerging surgical robotic technology. Surg. Endosc. **32**(4), 1636–1655 (2018)
3. Harky, A., et al.: The future of open heart surgery in the era of robotic and minimal surgical interventions. Hear. Lung Circ. **29**, 49–61 (2019)
4. McCarus, S.D.: Senhance robotic platform system for gynecological surgery. JSLS J. Soc. Laparoendosc. Surg. **25** (2021)
5. Rumolo, V., Rosati, A., Tropea, A., et al. : Senhance robotic platform for gynecologic surgery: a review of literature. Updates Surg. **71**, 419–427 (2019)
6. Gosrisirikul, C., Don Chang, K., Raheem, A.A., Rha, K.H.: New era of robotic surgical systems. Asian J. Endosc Surg. **11**, 291–299 (2018)
7. Seeliger, B., Diana, M., Ruurda, J.P., Konstantinidis, K.M., Marescaux, J., Swanström, L.L.: Enabling single-site laparoscopy: the SPORT platform. Surg. Endosc. **33**(11), 3696–3703 (2019)
8. Rassweiler, J.J., et al.: Future of robotic surgery in urology. BJU Int. **120**, 822–841 (2017)
9. Pusca, A., et al.: Workspace analysis of two innovative parallel robots for single incision laparoscopic surgery. Acta Tehnica Napocensis, **65**(II), 407–414 (2022)
10. Pisla, D., et al.: Singularity analysis and geometric optimization of a 6-DOF parallel robot for SILS. Machines **10**(9), 764 (2022)
11. Gherman, B., et al.: Singularities and workspace analysis for a parallel robot for minimally invasive surgery, 2010 IEEE (AQTR), pp. 1–6 (2010)
12. Plitea, N., et al.: Innovative development of surgical parallel robots. Acta Electronica, Mediamira Science, Cluj-Napoca, pp. 201–206 (2007)
13. Ulinici, I., Crisan, N., Vaida, C., Andras, I., Pisla, D.: Analysis and preliminary design of a new parallel robot for SILS. 2022 2022 IEEE Int. Conf. on Automation, Quality and Testing, Robotics (AQTR) (2022)
14. Ulinici, I., Vaida, C., Antal, T., Pisla, D.: Kinematics and workspace simulation of a new parallel robot for SILS. Acta Tehnica Napocensis, Series: App. Math. Mech. And Eng. **65**(II), 505–514 (2022)
15. Pisla, D., et.al.: Kinematics and workspace analysis of an innovative 6-DOF parallel robot for SILS. Proceedings of the Romanian Academy, Series A, **23**(3), 279–288 (2022)
16. Tucan, P., Vaida, C., Plitea, N., Pisla, A., Carbone, G., Pisla, D.: Risk-based assessment engineering of a parallel robot used in post-stroke upper limb rehabilitation. Sustainability **11**, 2893 (2019)
17. Papadakis, M., et al.: The WHO safer surgery checklist time out procedure revisited: Strategies to optimise compliance and safety. Int. J of Survery **69**(19), 22 (2019)
18. Vaida, C., Pisla, D., Schadlbauer, J., Husty, M., Plitea, N.: Kinematic analysis of an innovative medical parallel robot using study parameters. In: New Trends in Medical and Service Robots, Springer, Cham, Mechanism and Machine Science **39**, 85-99 (2016). https://doi.org/10.1007/978-3-319-30674-2_7