Chapter

Advanced Ergonomics in Laparoscopic Surgery

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Abstract

Applied ergonomics is very important in minimally invasive surgery (MIS), especially with the introduction of robotized techniques that have changed the surgeons' work conditions. However, the main aim remains the engineering to enable the compatibility of fulfillment of surgeons' tasks in a physical, logical, and organizational environment with security, comfort, and efficiency. Ergonomics contribution is oriented both to design and redesign utilized material and to work organization. Epidemiological studies have shown the appearance of musculoskeletal pathologies in surgeons performing MIS; therefore, it is relevant to identify the intensity, frequency, and duration of risk factors (posture, repeatability, level of effort, touch pressure, and vibration if relevant) associated with this profession. A further relevant consequence of the effort applied during MIS is local muscle fatigue (LMF), an important factor to consider in musculoskeletal pathologies. The aim of this chapter is to present different methodological approaches by employing most advanced technologies to define the most appropriate posture that surgeons should adopt during MIS to decrease LMF apparition risk level and at the same time to increase capacity to variate the posture without reducing the precision task performance.

Keywords: laparoscopy, ergonomics, musculoskeletal disorders

1. Introduction

Ergonomics can be defined as an interdisciplinary field of knowledge to study the characteristics, needs, and abilities of human beings, analyzing those aspects that affect the design of products and/or production processes. In all the applications, its objective is to try to adapt products, tasks, tools, spaces, and the environment in general to the biological characteristics, the capabilities, and the needs of the people in order to guarantee the safety and health of workers, users, and consumers as well as to increase their welfare and improve the production processes' efficiency [1].

Laparoscopic surgery as a technique of minimally invasive surgery began to be applied in the early 1990s and refers to surgical operations in the abdomen or pelvic cavity. Although this technique is very advantageous for the patient in comparison with an "open" surgical intervention [2], it is a technically challenging one for the surgeon [3, 4].

On the other hand, the "**fine handling**" associated with the performance of laparoscopic surgery techniques, related to very low frequency and relatively small amplitude motor patterns as movements are restricted due to the fixed holes through which the laparoscopic instruments are introduced, implies maintenance of the posture during relatively long intervals of time along with high levels of musculoskeletal effort and lack of comfort sensation.

Scientific studies have shown that the use of laparoscopic instruments contributes to significantly increase the activity of the deltoid muscle and at the same time the activity of the superficial flexor and common extensor digitorum [5, 6], promoting the appearance of local muscle fatigue in the upper extremities and in the neck area as well as numbness in the fingers [7–12].

To the aforementioned, it should be added that the minimally invasive surgery techniques also involve control of the position and orientation of the trunk and head, the segments whose mass is relatively large, reaching almost 50% of the total body and therefore involving a high muscular effort during relatively long time intervals. In addition, surgeons have to manipulate instruments that are not designed with ergonomic usability criteria, since the level of force and contact pressure implied by their use (clamp and grip) are unknown. Finally, the use of monitors during surgical operations implies an additional difficulty for surgeons as there is no tactile interaction with the organs undergoing the operation [13, 14].

In this scenario, it is very common to adopt and maintain awkward postures for relatively long periods of time, which cause a high level of physical load associated with the intervention of the muscles that control the involved joints of the locomotor system. These factors can cause discomfort and musculoskeletal pain or even disorders that can lead to permanent disability and/or need for surgical intervention (**Figure 1**).

This type of pathology develops progressively in **stages**, so that in the first stage, moderate fatigue and initial discomfort that are usually moderate are observed. In the second stage, there are occasional discomforts in the posture and mild pain that disappears with a good rest. Then, as a consequence of the continued exposure to the risk factors, pain and other symptoms that persist almost throughout the day appear causing a process of progressive degradation that leads to more severe pain

Figure 1.
Neck surgery (left) and Surgery training (right).

and ends up compromising the daily activity. This ends in a chronic disability that reduces the normal physical abilities of the person and seriously affects his/her quality of daily life.

Since two decades, the European Agency for Safety and Health at Work [15], at the request of the European Commission, has issued two reports on musculoskeletal disorders and injuries related to work. In these reports, the social and economic dimension of musculoskeletal pathologies has been confirmed as well as the need to establish standardized scientific criteria for the evaluation of their risk factors. Secondly, the reliability of the epidemiological data is questioned and the reconsideration of experimental studies is recommended as there is no consensus on the confirmation of the appearance of local muscle fatigue as a risk factor in association with the adoption of forced working postures and the performance of repetitive movements. In this sense, ergonomic intervention based on scientific work is recommended for the development of strategies for the evaluation and prevention of risk factors for musculoskeletal pathologies.

The objective of this chapter is, starting with the results of an epidemiological study (Nordic Questionnaire), to present the results of the research work carried out by the collaboration between the Jesús Usón Minimally Invasive Surgery Centre and the BioẼrgon research group during the last 15 years based on the methodology of ergonomics and using the instrumental techniques of Biomechanics of Human Movement to contribute to investigate the level of physical effort borne by surgeons and to establish ergonomic criteria to improve the working conditions of surgeons, as well as to establish ergonomic design criteria for laparoscopic material by analyzing different tasks in laparoscopic surgery in conjunction with the motor behavior of surgeons.

In this sense, the results of the research are useful to manage organizational and ergonomic decision-making with the aim of introducing an ergonomic conception of laparoscopic surgery processes to improve surgeons' occupational health and quality of life. The application of these measures requires to previously identify and evaluate the risk factors. This means to select the tasks and jobs with exposure to risk of injury, to study which is the level of exposure in each of them, and to decide in which cases it is necessary to apply correction measures.

The possibilities offered by **Biomechanics** to raise and solve problems related to the improvement of health and quality of life have consolidated it as a field of knowledge in continuous expansion, capable of providing scientific and technological solutions. On the other hand, the industrial projection of Biomechanics has reached several sectors, providing the basis for the conception and adaptation of numerous products, for diagnostic techniques and for the evaluation of human motor skills.

The objective of the applied research in the occupational field is to analyze working conditions, especially the interface "man-workplace" or "man-machine" as a way to prevent discomfort and/or occupational pathologies, to reduce fatigue and increase the comfort and to generate criteria for the design of tools and jobs according to the characteristics of the users and the tasks to be performed.

2. Epidemiology study

The epidemiological study enables collection of data regarding the incidence of musculoskeletal pathologies in laparoscopic surgery and the risk factors, which favor their appearance [16].

The study was conducted on a sample of 52 surgeons (35–65 years), (7.31 ± 3.30 years of experience) in the techniques of laparoscopic surgery and (12.9 ± 6.7) hours per week dedicated to them.

The standardized Nordic Musculoskeletal Questionnaire (NMQ) modified by the Health and Safety Executive (HSE) of the United Kingdom was used (**Figure 2**) [17, 18]. The epidemiological study also included the procedure of the National Institute of Health and Safety at Work of the USA [19], which allows to identify the musculoskeletal disorders, the conditions which cause them, as well as the perception of the workers.

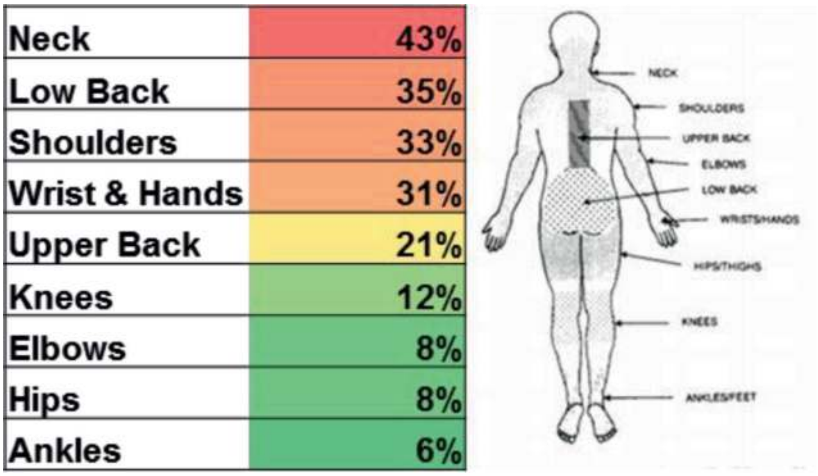
According to results of the study, 58% of the survey respondents have suffered **neck** pain (43% in the last 12 months) and 66% attribute it to their activity at work. The frequency of pain in the neck area is high (**Figure 2**). Occasionally, pain is intense to very intense, though in most cases, it is of lower intensity (**Figure 3**).

Thirty-seven percent of the survey respondents have suffered from **shoulder** pain (33% in the last 12 months) and 75% associate it with their activity at work. The frequency of shoulder pain is high with approximately 50% of the subjects reporting intense to very intense pain and with the remaining subjects reporting pain of lower intensity (**Figure 4**).

As regards the **back**, 42% of subjects have suffered pain or discomfort in the upper part (21% in the upper part and 35% in the lower part in the last 12 months); 71% of the survey respondents attribute their back pain to activity at work and 19% have even missed work for this reason. Pathologies of the back occur with a considerably high frequency (**Figure 5**).

Thirty-seven percent of subjects have suffered from pain in the **wrists** and **hands** (31% in the last 12 months). Although the frequency is considerably low (**Figure 6**), 17% have suffered from pain in these areas at least once a month. Although they did not miss work, 6% of survey respondents have seen their work performance affected for at least 1 week due to pain in the wrists and hands.

It is important to highlight the relevance for surgeons of the position they adopt during minimally invasive surgical procedures. In personal interviews, surgeons have stated that the position adopted during surgery is substantial to better perform the intervention (96%), they consider training being necessary in association with the adoption of a comfortable posture during the intervention (88%), and they indicate that they are "forced" to operate by adopting an uncomfortable position according to their subjective perception (46%). The data suggest that the forward inclination of the body is performed unconsciously (67% of respondents). On the other hand, 61% surgeons think that the coordination of the posture



Neck	43%
Low Back	35%
Shoulders	33%
Wrist & Hands	31%
Upper Back	21%
Knees	12%
Elbows	8%
Hips	8%
Ankles	6%

Figure 2.
Anatomical parts of the body analyzed in the epidemiological study and percentage of musculoskeletal discomfort by anatomical regions adapted from [17].

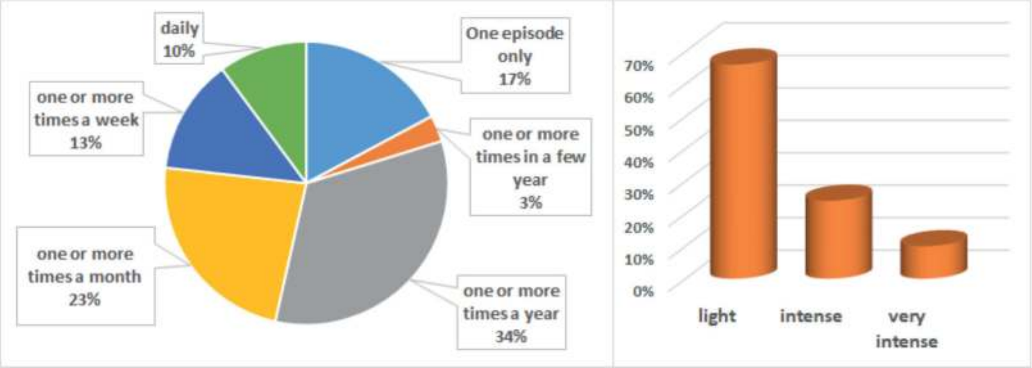


Figure 3.
Frequency of pain appearance and pain intensity in the neck area.

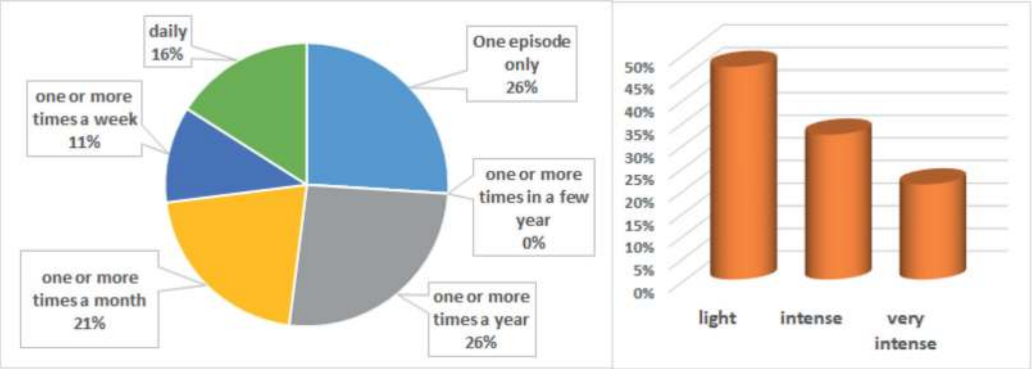


Figure 4.
Frequency of appearance and intensity of shoulder pain.

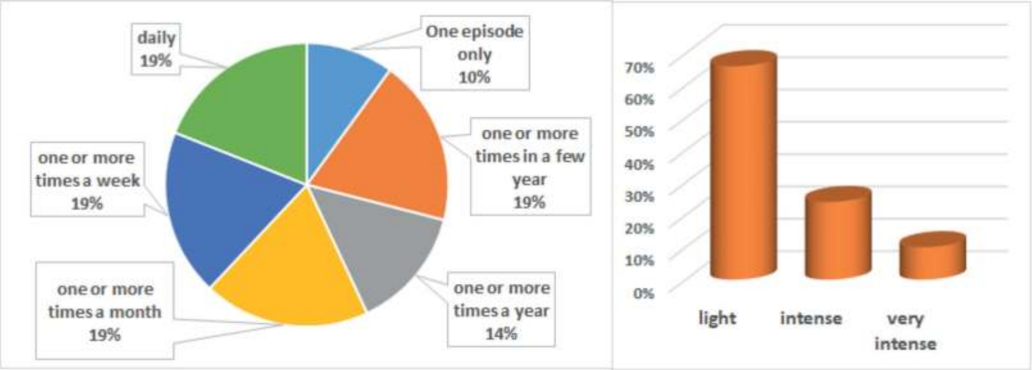


Figure 5.
Frequency of appearance and pain intensity in the back area.

during the surgical procedure appears naturally while for the remaining 39%, it is learned. Furthermore, data suggest that the arrangement of the equipment in the operating room is the cause of the adoption of forced trunk postures (80% of the respondents). These forced postures are due to the distance to the operating table (15%) and due to its height (13%). The placement of the monitor also implies the adoption of an awkward posture (57%). Sixty-two percent of surgeons have problems due to the prolonged maintenance of the posture, 68% indicate the adoption of uncomfortable postures, and 70% indicate the adoption of forced postures. Finally, surgeons were asked about comfort in the use of surgical instruments and

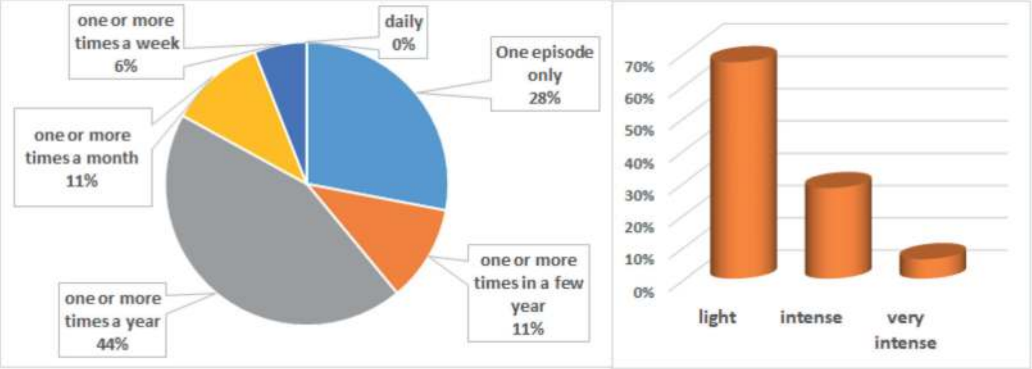


Figure 6.
Frequency of appearance and pain intensity in the wrist-hand area.

they reported having experienced difficulties with handling the needle holder (22%), handling the suction-irrigation equipment (15%), with the view of the monitor (8%), with scissors (6%), with diathermy equipment (6%), and with the dissector (4%).

3. Anthropometry

The adaptation of the laparoscopic surgery's environment and of the equipment based on ergonomic criteria must take into account that the seated position cannot be adopted because it conditions the angle of incidence of the instruments [20] and the morphological characteristics of the users. Anthropometry provides information regarding the dimensions of the human body in a certain (static) position, as well as the ranges of movement of the body parts, reach, trajectories, surfaces, and volumes of movement (functional). Although different types of anthropometers have been developed over the last decades, BioÈrgon Research Group has developed a procedure based on three-dimensional photogrammetry of BiomSoft 2.0 software [21] (**Figure 7**) to obtain anthropometric data assisted by a Vitus Smart XXL® system (human solutions) of full-body scanning, capable to provide anthropometric data in industrial quantities with ±1 mm level of accuracy, in accordance with the international standard DIN EN ISO 20685 (**Figure 8**).

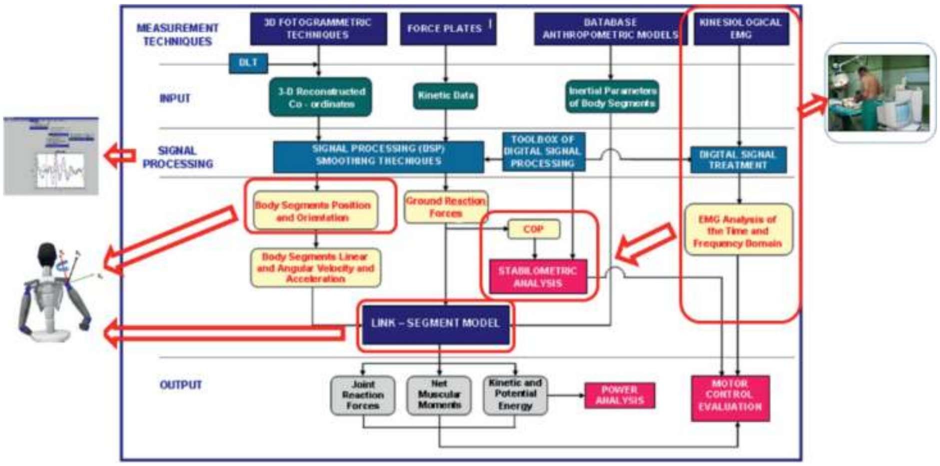


Figure 7.
BiomSoft 2.0 flow chart.

Figure 8.
A 3D scanner for anthropometry.

The obtained information is relevant to formulate criteria and recommendations for ergonomic intervention in the laparoscopic surgery scenario, such as working in a standing position with sufficient space for the hands and with properly dimensioned tools especially in the handles, to avoid tensions in the arm and wrist and to allow handling of the tools to be comfortable for the hands. The ISO 6385 [22] standard recommends adapting the height of the work surface to the user's dimensions for tasks, having enough space for body movements, having tables and controls within reach, and providing tools with handles adapted to the user's hand. The required levels of strength should be within the desirable limits, and the movements of the body should be natural and soft. Finally, the movements of the trunk should not introduce excessive inclinations and/or torsions.

4. Characterization and motor control of posture

4.1 Ovako working posture analysis system

As during the performance of laparoscopic surgery a standing posture is adopted, it is important to regulate and adapt the height of the operating table, the height of the monitor, and its orientation and the space for the feet to be able to operate near the surface of the operating table to the morphological and functional characteristics of the surgeon. The placement of the elements in the surgeon's environment should facilitate the adoption of a comfortable posture, especially in the early stages of learning laparoscopic techniques, avoiding excessive inclinations and/or torsions of the trunk and head, as well as abduction of the shoulders. In this context, characterization studies of the adopted position and its consequences during simulations of laparoscopic operations have been carried out. In the first phase of performed studies, the application of the OWAS protocol [23] was used as a standardized process to characterize the level of risk for tasks and for postures that were forced, nonrepetitive, and without defined work cycles, taking into account the posture of the trunk, arms, and legs as well as depending on the level of the load or force exerted by the surgeon. This process allowed to assess the level of risk for surgeons caused by the maintenance of the analyzed postures for a prolonged period of time. The position of 13 surgeons (four women and nine men) with different levels of experience and specialties was analyzed. The surgeons performed a simulation of a 60-minute laparoscopic surgery at the Jesús Usón Minimally Invasive Surgery Centre, and the adopted position was coded every 20 seconds (**Figure 9**) using a 3D video photogrammetry.

The effective time of the operation was identified as the time during which the subject looks at the screen and handles the surgical instruments with both hands (**Figure 10**). Interruptions could be due to the training process, change in surgical instruments, change in simulation material in the pelvitrainer, and distracting attention.

In the obtained data (**Figure 11**), it can be observed that during the procedures, 12 of the surgeons adopted a posture with **level 2** risk, meaning that intervention is necessary, although not immediate.

The position of this level adopted by a greater number of surgeons sometimes during the intervention (**10 of the surgeons**) was coded as **2121**, which corresponds to a posture with the back inclined, the arms below the shoulder, and standing with both legs straight with a light load ≤10 kg. Furthermore, four surgeons adopted a posture with **level 3** risk of musculoskeletal injuries, implying that the working method should be modified as soon as possible. The posture of this level adopted by a greater number of surgeons sometimes during the intervention was coded as **4231**, which corresponds to a posture with the back bent and turned, one arm above the shoulder, standing with one straight leg, and with a force ≤10 kg. Only one surgeon adopted a posture with a **level 4** risk of musculoskeletal injuries, meaning that corrective measures must be taken immediately.

4.2 3D photogrammetry

As observed previously, it is necessary to use instrumental techniques with a greater discriminatory capacity to characterize the position adopted by surgeons due to the fact that some movements such as bending and rotation of the trunk and head as well as flexion and abduction of the arms have been detected. 3D photogrammetry was utilized in order to quantify the posture of the body segments in 3D. The mechanical model (**Figure 12**) that was used to

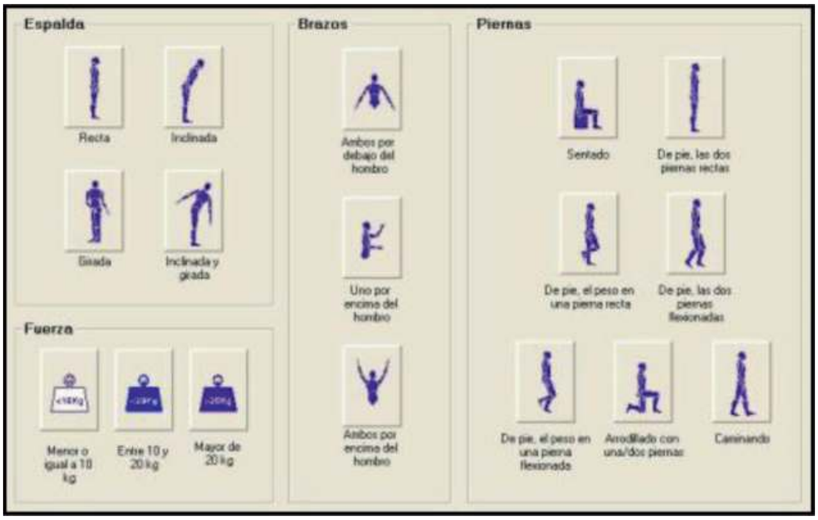


Figure 9.
OWAS protocol (ergo/IBV software®).

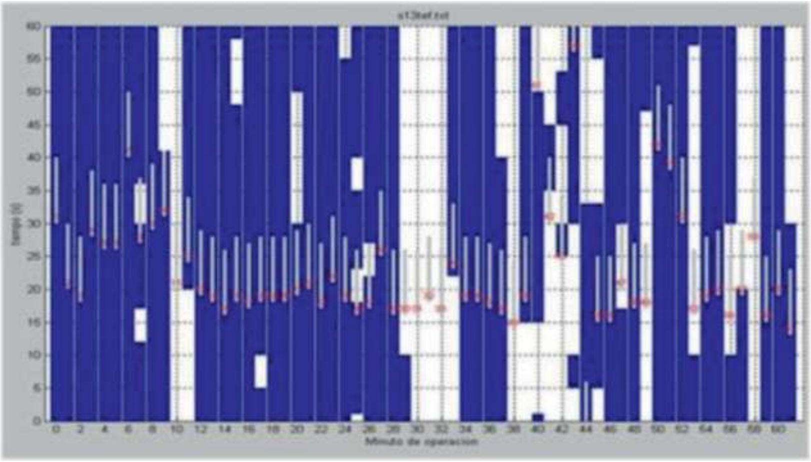
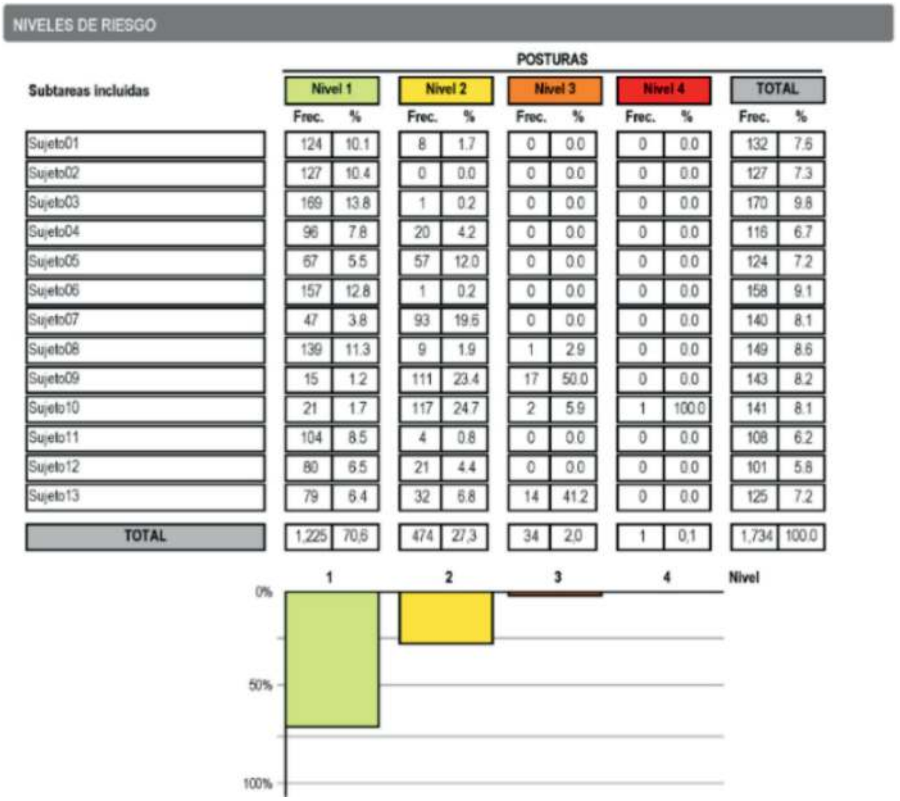


Figure 10.
Recorded surgery time. Blue: effective time and white: EMG record time.



NIVELES DE RIESGO

Subtareas incluidas	POSTURAS									
	Nivel 1		Nivel 2		Nivel 3		Nivel 4		TOTAL	
	Frec.	%	Frec.	%	Frec.	%	Frec.	%	Frec.	%
Sujeto01	124	10.1	8	1.7	0	0.0	0	0.0	132	7.6
Sujeto02	127	10.4	0	0.0	0	0.0	0	0.0	127	7.3
Sujeto03	169	13.8	1	0.2	0	0.0	0	0.0	170	9.8
Sujeto04	96	7.8	20	4.2	0	0.0	0	0.0	116	6.7
Sujeto05	67	5.5	57	12.0	0	0.0	0	0.0	124	7.2
Sujeto06	157	12.8	1	0.2	0	0.0	0	0.0	158	9.1
Sujeto07	47	3.8	93	19.6	0	0.0	0	0.0	140	8.1
Sujeto08	139	11.3	9	1.9	1	2.9	0	0.0	149	8.6
Sujeto09	15	1.2	111	23.4	17	50.0	0	0.0	143	8.2
Sujeto10	21	1.7	117	24.7	2	5.9	1	100.0	141	8.1
Sujeto11	104	8.5	4	0.8	0	0.0	0	0.0	108	6.2
Sujeto12	80	6.5	21	4.4	0	0.0	0	0.0	101	5.8
Sujeto13	79	6.4	32	6.8	14	41.2	0	0.0	125	7.2
TOTAL	1,225	70,6	474	27,3	34	2,0	1	0,1	1,734	100.0

Figure 11.
Report of risk levels.

record the spatial coordinates of the anatomical markers (15 real + 3 virtual) was defined according to the standardized procedures of the kinematic analysis of the International Society of Biomechanics [24]. In this sense, the position was characterized in terms of the Euler angles [25] and the "Joint Coordination System" (JCS) [26], which allow to determine the variation of the orientation of a segment in three dimensions with respect to a local RS. Three markers associated with the monitor and three markers associated with the operating table were added to the mechanical model (**Figure 12**).

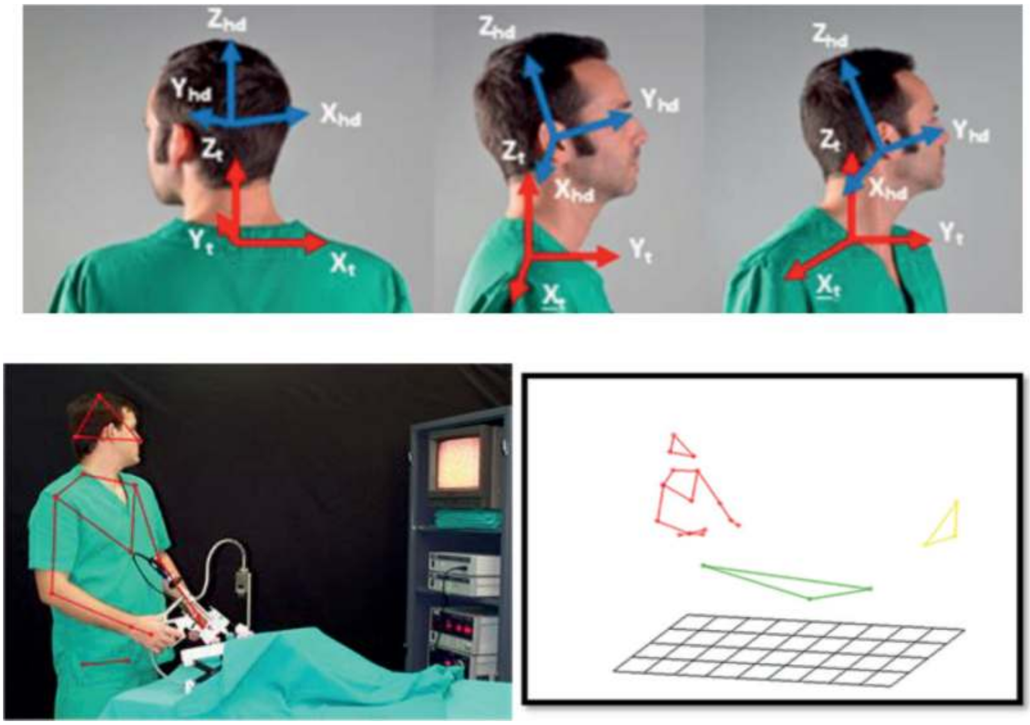


Figure 12.
Mechanical model used for the evaluation of posture by 3D photogrammetry.

The sequence of turns used for the head was Zt-Yh-Xh (**Figure 12**) of the JCS method. Axes are defined as follows:

i. Zt axis of the coordinate system associated with the trunk, which represents the axis with respect to which the flexion (negative)/extension (positive) movement takes place.

ii. Yh axis of the head representing the axis with respect to which the right (negative)/left (positive) rotation movement takes place.

iii. Xh axis has the direction of the "vector product" of the other two axes, representing the axis with respect to which the right (negative)/left (positive) inclination movement takes place in the articulation.

For the body segment of the shoulder, the sequence of turns Yt-Xh-Yh (**Figure 13**) of the Euler angles is as follows:

i. First rotation: the Yt axis of the coordinate system associated with the trunk that represents the axis with respect to which the azimuthal angle takes place (0° is abduction and 90° is forward flexion).

ii. Second rotation: the Xh axis of the humerus that represents the axis with respect to which the lifting movement of the humerus takes place (elevation: positive).

iii. Third rotation: the Yh axis of the humerus that represents the axis with respect to which the internal (positive)/external (negative) rotation movement of the humerus takes place.

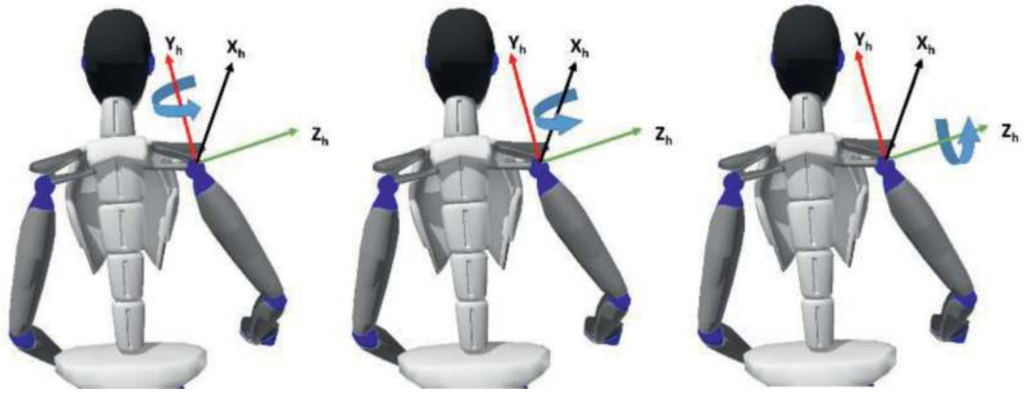


Figure 13.
Definition of the rotations of the right upper limb.

The measurements performed to characterize the position adopted by surgeons during the simulation of laparoscopic operations allowed for the first time to quantify the order of magnitude of the relative orientation of the body segments in laparoscopic surgery. The results obtained on the shoulder joint show that the range of the elevation angle oscillates between 11 and 46.1° with an average of 26.2° ± 7.8 (coeficient of varation (CV) 30%) for the skillful arm, while for the nonskillful arm, it varies between 9.1 and 52.6° with an average of 27.1° ± 10.1 (CV 37%). In both cases, the coefficient of variation is high, a fact that demonstrates the high variability in the position adopted by the surgeons during the surgical procedure as a consequence of the nonexistence of ergonomic criteria for the configuration of the work environment. A high percentage of surgeons operate with an elevation angle close to or greater than 30° associated with the appearance of local muscle fatigue in the shoulder as suggested by other studies [3, 27]; therefore, it is recommended that the range of elevation of the arms is below 30°. The position of the arm is directly related to the height at which the laparoscopic instruments are manipulated. These data suggest adapting the surgical environment to the characteristics of the surgeon taking into account the order of magnitude of the variability found in the studies performed.

As regards the posture of the head, the following values were found: flexion of 14.76° ± 9.86 (CV 67%), extension of 2.8° ± 2.6 (CV 93%), left lateral inclination of 4.75° ± 4.09 (CV 86%), right lateral inclination of 10.71° ± 6.17 (86% CV), internal rotation of 14.21° ± 12.18 (86% CV), and external rotation of 9.31° ± 7.17 (77% CV). The results confirm that the head barely moves (range of motion) as a consequence of the observation of the monitor, and therefore, the muscles that intervene in the maintenance of the posture during relatively long time intervals can experience fatigue [28–30].

As could be seen so far, it is very important to take into account the high variability of the geometric parameters associated with the posture adopted by the analyzed surgeons. Therefore, the question arises whether this variability is "biopositive" or "bionegative" from the point of view of ergonomics and of the prevention of musculoskeletal pathologies of personnel as a consequence of postural and muscular effort.

4.3 Variability study: uncontrolled manifold analysis

As a consequence of what has been described in Section 4.2, it is important to study the variability of the posture in order to test whether variability in upper limbs-joint configuration stabilizes or destabilizes head posture on the sagittal plane as its position is constrained by the displacement of the monitor during conventional laparoscopy (LAP) and Laparoendoscopic Single Site (LESS) surgery approaches. Also, the introduction of a framework to quantify joint coordination and its influence on the posture adopted by surgeons seems to be relevant. Therefore, an uncontrolled manifold (UCM) hypothesis model has been proposed that allows to quantify, globally, kinematic variability in task-relevant and task-irrelevant components and to determine whether the analyzed laparoscopic tasks are performed in healthy ranges or not. The UCM provides a quantitative approach to analyze the influence of imposed constraints, e.g., workplace layout and instruments design on the postural strategy that surgeons choose to accomplish surgical tasks, and it allows to map the variance of three individual joint angles onto the head position variance. Also, it allows separation of the combinations of the mentioned angles that are equally able to stabilize the head position within an acceptable margin of error for those combinations that are irrelevant for the ongoing task (**Figure 14**).

The UCM framework has been used recently to examine whether teleoperation with the da Vinci Si Surgical System manipulator (grip fixture attached to master manipulator) changes the structure of joint variability relative to the freehand (holding the grip fixture alone) in experienced and novice surgeons [31] as well as to analyze whether joint angles cooperate to adjust head position during laparoscopy work [32] (**Figure 15**).

It was shown that the effect of teleoperation on hand movements' stabilization depends on experience and that the head control variable defines an uncontrolled manifold, i.e., joint configurations of upper arm during laparoscopy do not destabilize head position. The motor redundancy, due to the numerous degrees of freedom of the human locomotor apparatus, compared with the substantially lower anatomical constraints that are imposed by the structure of the musculoskeletal system at the level of the joints, gives the surgeons the possibility to adopt an infinite number of postures during work and consequently the ability to execute countless voluntary motor patterns in order to accomplish their tasks.

Eight right-handed experienced surgeons in laparoscopic surgery (>100 laparoscopic procedures) and LESS surgery (>20 procedures using LESS approach) voluntarily accepted to participate in the study. Subjects performed a dissection of the serosa layer on an ex vivo porcine stomach inside a laparoscopic box trainer for

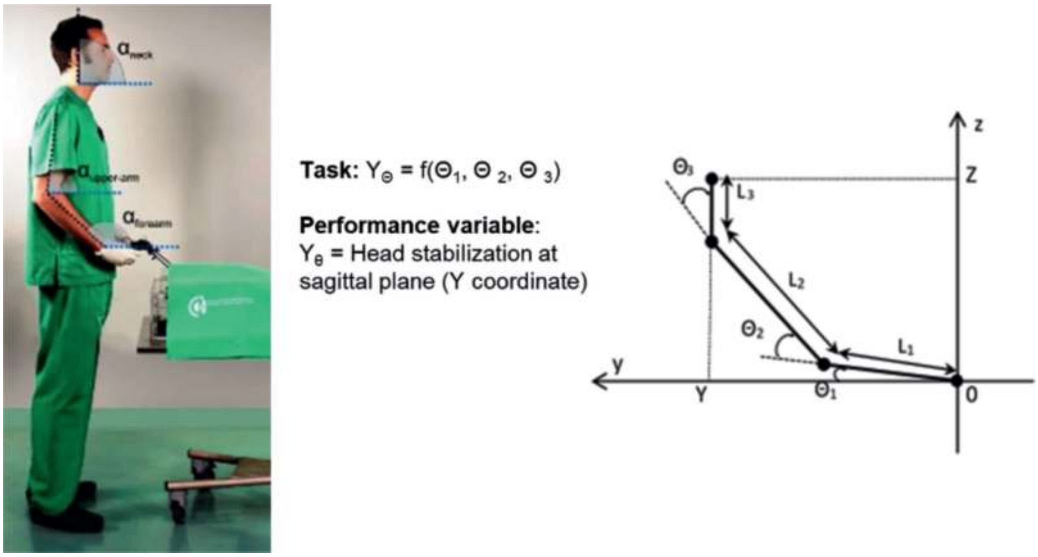


Figure 14.
Mechanical UCM model.

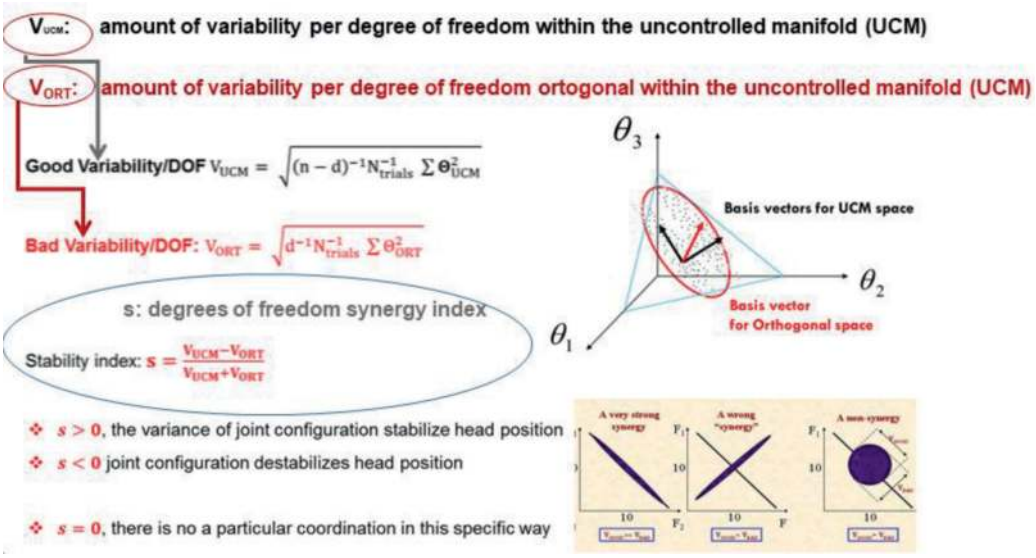


Figure 15.
UCM resume.

10 minutes. This task was carried out by both laparoscopic surgical approach (LAP) and by LESS surgery [33]. A 3D photogrammetry was used to calculate the spatial coordinates of anatomical markers, using the same model as described in Section 4.2. The 3D coordinates of digitized points were obtained using the algorithm known as direct linear transformation (DLT) and were specified with respect to the defined origin of the global reference system. The 3D coordinates were obtained for a total of 40 events ($N = 40$), an event in every 15 seconds of surgical activity. For the same events, the posture of the head was defined with respect to the trunk, considering posture as the position and orientation of body segments. The trunk and head body segments were defined as solids, and their spatial position and orientation were obtained fixing them to segmental reference frames (SRF). This process allows the measurement of the posture adopted by surgeons in terms of clinically interpreted position and orientation of body segments. The results of the study show that kinematic redundancy enables surgeons to adopt an appropriate posture during surgical tasks, allowing them to avoid uncomfortable postures. However, other constraints other than the anatomical ones may have an impact, in particular joint configurations, i.e., workspace layout and instrumental design. Therefore, the goal of the UCM analysis was to test whether variability in upper-limb joint configuration during two different surgery approaches stabilized or destabilized head posture on the sagittal plane. Although the intertrial variability in joint configuration space should be organized to stabilize manual operation-task movements, by definition, it could also be organized to stabilize other important controlled variables as well. The head posture is a plausible candidate as its position is constrained by the displacement of the monitor. The results of the UCM analysis showed a positive degrees of freedom synergy index indicating that the covariation of the upper-limb joint angles stabilizes the head posture of the surgeons in the anterior-posterior direction. This synergy is stronger in some surgeons (**Figure 16**).

Even though the synergy index takes different values between the LAP and LESS approach (**Figure 17**), there was not a statistically significant difference in the synergy index between the LAP and LESS approach for the UCMs of both the left ($t_{(7)} = 1.76$ and $p = 0.12$) and right joint spaces ($t_{(7)} = 0.127$ and $p = 0.902$). As can be seen in the results of 3D kinematics of the posture of the head with respect to the trunk (**Figure 18**), there is a high variability of the postures adopted by

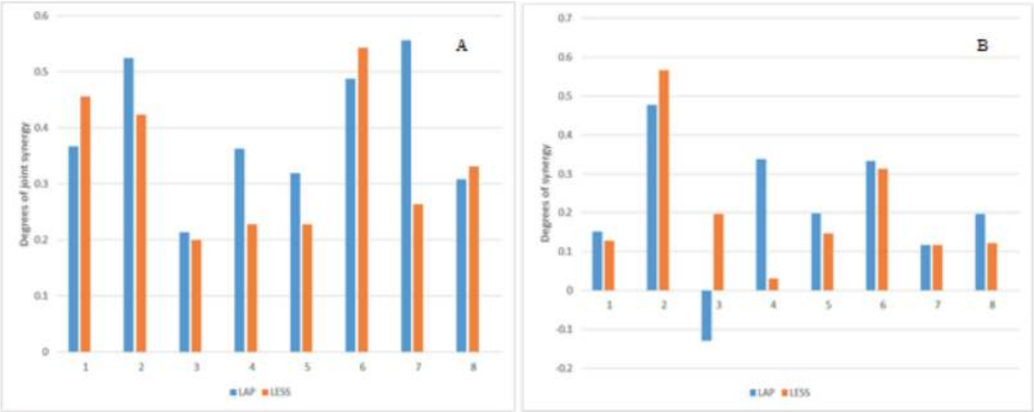


Figure 16.
UCM synergy. (A) Left body side and (B) right body side.

Figure 17.
LAP (left) vs. LESS (right).

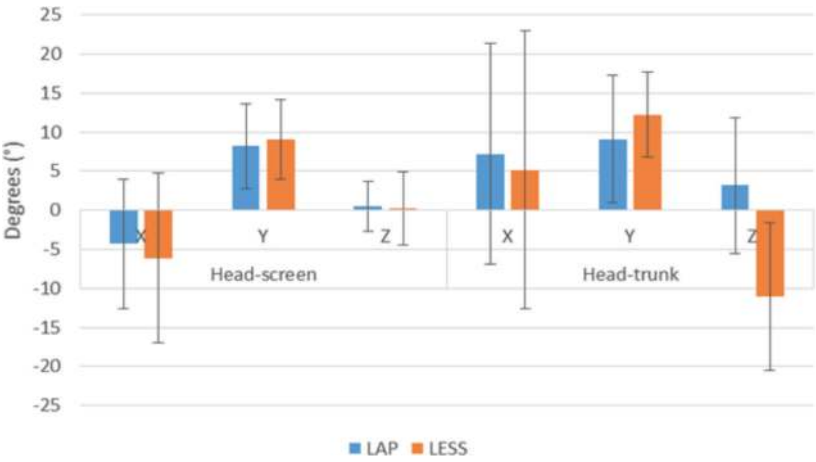


Figure 18.
Results of variability of 3D neck rotation depending on monitor and trunk.

the surgeons. This is due to the fact that surgeons are free to adopt their postures according to their personal judgment. Kinematics of surgeon heads' posture with respect to the trunk indicates high variability because of the adoption of the posture according to the subjective perception. Upper-body joint variability quantified using the framework of the UCM hypothesis allowed to separate the combination of joint angles that were equally able to stabilize mean head posture on sagittal plane for those solutions that destabilized head mean posture.

4.4 Inertial unit measurement system

In the last few years, introduction and use of inertial sensors in the analysis and characterization of posture variability in the context of minimally invasive surgery has been a great advance in biomechanics methodology, as 3D photogrammetry requires a lot of time for digitation of images. This has been the most important reason for BioẼrgon Research group to record and analyze laparoscopic procedures in 3D using this technology, being a pioneer and probably the only one group to use it. Undoubtedly, this is much more an efficient instrumental technique for the characterization of posture in minimally invasive surgery [34]. In this sense, a study using the commercial system XSens MVN Biomech (**Figure 19**) was carried out in the Jesus Usón Minimal Invasive Surgery Center. Eight surgeons participated in the study (four novices and four experts) and performed 24 simple sutures with conventional instruments. The results obtained regarding the position of the surgeons corroborate the high variability found in the studies carried out with 3D photogrammetry. The values found show CV greater than 70% in all joints and especially in the wrist joint flexion-extension and radial and ulnar deviation (**Figure 20**).

Figure 19.
Sensorized surgeon with inertial measurement units (IMUs) and biomechanical model used by XSens.

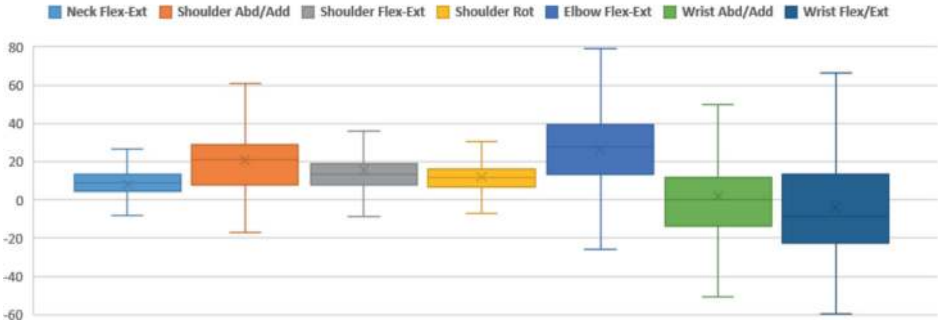


Figure 20.
Results from capture of surgeons' posture performing a simple suture.

5. Effort evaluation

The level of effort involved in the development of work tasks in a particular job is a risk factor for musculoskeletal pathologies. In this sense, different instrumental techniques and electronic measurement systems are used to evaluate the level of effort, such as electromyography (**Figure 21**), which allows to characterize the intensity of muscle intervention of a specific muscle and detect muscle fatigue if it occurs. Force sensors such as force plates allow to measure the reaction force with the environment, and contact pressure sensors allow to measure the pressure that the surgeon experiences when holding and manipulating laparoscopic instruments, which also constitutes a risk factor. In the studies carried out by the BioẼrgon Group, surface electromyography (EMG) has been used as an instrumental technique to analyze the relationship of the position adopted by the surgeons.

5.1 Surface electromyography

Electromyographic data were recorded with the surface electrode and were carried out to establish upper trapezius and middle deltoid intervention as neck-shoulder area stabilizers. Thirteen surgeons (four woman and nine men), with different experience levels, performed a surgery simulation of 60 minutes duration at the Jesús Usón Minimally Invasive Surgery Centre, as mentioned in Section 4. The analysis of the electromyographic data in the frequency domain made it possible to detect median frequency (f_{median}) of the appearance of local muscular fatigue (LMF), which is one of the risk factors that cause discomfort and musculoskeletal disorders. Surgery time was divided into 60 intervals with a duration of 1 minute each. In each interval, an EMG record was made, meaning that a period of 1 minute passed between one record and the next. Results show that LFM appears in 62% of analyzed surgeons in part of the analyzed muscles (**Table 1**).

Therefore, it would be advisable to pay special attention to work-rest guidelines, especially for female surgeons. Taking into account the results of the kinematic analysis, it can be stated that the combination of abduction with the elevation of the arms is associated with a high activity of the deltoid and results in the appearance of muscle fatigue that was detected. The appearance of local muscle fatigue has also been confirmed in another study conducted in collaboration between BioẼrgon Group and CCMIJU, where the same methodology as described above was used. Eight experienced surgeons in laparoscopy and LESS (>100 laparoscopic

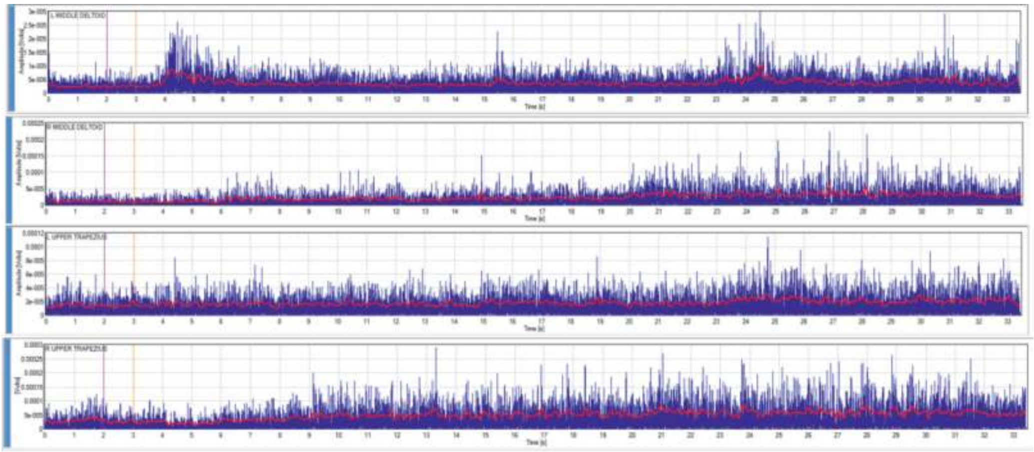


Figure 21.
EMG signal. Blue: rectified signal and red: RMS_{EMG}.

	p-Value	T	r	R^2
01 RT f_{MEAN} 40–60	0.0023**	−4.21	−0.81	66.32%
02 RT f_{MEAN} 20–40	0.0023**	−3.77	−0.72	52.20%
02 RT f_{MEAN} 40–60	0.0085**	−3.19	−0.69	48.00%
02 LT f_{MEAN} 20–40	0.0038**	−3.51	−0.69	48.66%
03 LT f_{MEAN} 0–20	0.0000***	−5.38	−0.79	63.00%
03 LD f_{MEAN} 20–40	0.0025**	−3.54	−0.65	42.46%
04 RD f_{MEAN} 20–40	0.0302*	−2.36	−0.50	24.75%
04 RT f_{MEAN} 40–60	0.0106*	−3.45	−0.79	63.01%
06 LD f_{MEAN} 20–40	0.0000***	−5.95	−0.85	73.13%
07 RD f_{MEAN} 40–60	0.0095**	−3.20	−0.71	50.60%
08 LT f_{MEAN} 20–40	0.005**	−3.49	−0.72	52.65%
08 LD f_{MEAN} 20–40	0.0092**	−3.15	−0.69	47.45%
09 LD f_{MEAN} 20–40	0.0375*	−2.56	−0.69	48.38%
11 TD f_{MEAN} 0–20	0.0358*	−3.63	−0.90	81.50%

$^*p \le 0.05$.
$^{**}p \le 0.01$.
$^{***}p \le 0.001$.

Table 1.
Results of LMF observed cases. RT, right trapezius; LT, left trapezius; RD, right deltoid; LD, left deltoid.

procedures and >20 single incision procedures) performed a dissection of the serosa layer of a porcine stomach, attempting to separate the serosa layer from the muscular layers. The single port approach led to significantly greater muscle activity in the paraspinal muscles of the right middle cervical portion and the upper right trapezius than the conventional laparoscopic approach. In both approaches, surgeons showed muscle fatigue in at least one of the analyzed muscles. During dissection using a conventional laparoscopic approach, seven of the surgeons reported muscle fatigue in the upper left trapezius. In the case of the single port approach, seven of the surgeons showed muscle fatigue in the right middle trapezius and they showed increased muscle activity in the paraspinal muscles of the right middle cervical portion and in the right upper trapezius. In both procedures, significant EMG spectral shifts toward lower frequencies were seen in at least one muscle in all surgeons, except for one surgeon during LESS. Significant differences were found for the right upper trapezius and mid-cervical paraspinal muscles ($F[1, 7] > 6.65$ and $p < 0.05$). With the introduction of the instruments with new features and design [35] in the market, comparative studies are carried out with the aim of verifying their functionality and usability. One of the performed studies involved three experienced laparoscopic surgeons carrying out three intracorporeal cutting tasks on a box trainer using a conventional laparoscopic Maryland dissector and a pair of scissors as well as their equivalent r2 DRIVE instruments. Surgeon ergonomics were evaluated through analysis of the surface electromyography of trapezius, deltoid, and paravertebral muscles. Results show that muscle activity of the surgeons was significantly higher for the left deltoid muscle and bilaterally for the muscle trapezius when the novel instruments are used (**Figure 22**).

Finally, twelve laparoscopic partial nephrectomies of the caudal pole in an experimental porcine model were performed by two experienced laparoscopic surgeons, using conventional laparoscopic instruments and laparoscopic instruments with

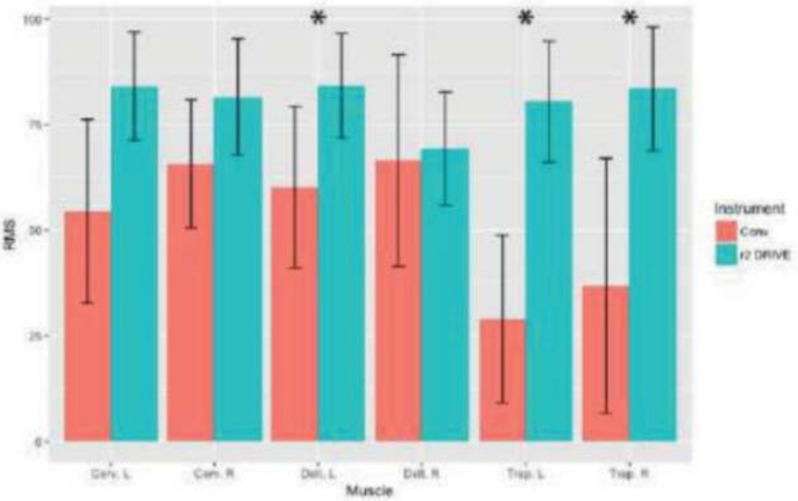


Figure 22.
Muscle activity (RMS_{EMG}) of the paravertebral, deltoid, and trapezius muscles during the use of the conventional and r2 DRIVE laparoscopic instruments.

articulated handle with rings. Results confirmed that although the novel instruments have a new design that incorporates ergonomic criteria, they produced localized muscle fatigue in the left deltoid and bilaterally in the lower trapezius muscles when using the dissector. Even though the surgeons did not notice differences in use and physical workload, the new instruments led to localized muscle fatigue.

5.2 Localized contact pressure

Finally, the last relevant risk factor in the surgical context is **localized contact pressure** (**Figure 23**) that can cause nerve injuries and injuries of the tissue below the skin, especially when it is carried out in a repeated way or when it is maintained for a long time, situations that typically occur during laparoscopic surgery. Sensors and electronic systems are used to record the level and distribution of pressure during the manipulation of laparoscopic instruments (**Figure 23**). This technology allows to evaluate if the pressure levels are harmful for the surgeon and to draw conclusions on the most suitable design of the contact surfaces of the laparoscopic material [36].

Two studies performed in collaboration between CCMIJU and BioĒrgon Group surgeons carried out a urethrovesical anastomosis on a porcine model using a novel handheld robotic laparoscopic instrument and a conventional axial handheld laparoscopic needle holder (two experienced surgeons >100 laparoscopic procedures in the first study and five experienced surgeons in the second one). On the one hand, results show that the pressure exerted by the thumb is notably higher during the use of the robotic instrument. This is due to the interaction with the controls installed on the handle of the instrument. The pressures registered by the index and middle finger as well as the palm of the hand are very similar when using both types of laparoscopic instruments, except for the thumb finger [36]. On the other hand, results showed that the force exerted by the distal phalange of the index finger was significantly higher on the conventional handle as compared to the force exerted on the handle of the robotic instrument. The palm of the hand was the area that received the highest pressure in both instruments, but for longer periods when using the robotic instrument. However, further studies are required to analyze the pressure applied on these laparoscopic instruments by other parts of the hands, such as the intermediate phalanges of the thumb, index, and middle fingers [37].

Figure 23.
Contact pressure measurement, generated during the use of laparoscopic instrumental.

6. Conclusion

In this chapter, results of the research work carried out by the collaboration between the BioẼrgon Research Group and the Jesús Usón Minimally Invasive Surgery Centre (CCMIJU) during the last 15 years have been presented. This research was performed based on the methodology of ergonomics, using the instrumental techniques of the Biomechanics of Human Movement to analyze the presence of risk factors of musculoskeletal pathologies in the multiple tasks of laparoscopic surgery and to establish ergonomic criteria that allow to improve the working conditions of surgeons, as well as the design of the laparoscopic material. Results of the research are useful for organizational and ergonomic decision-making, aimed at the introduction of an ergonomic conception of laparoscopic surgery processes for the improvement of occupational health and quality of life of the surgeons. Factors and levels of risk of suffering musculoskeletal injuries in the neck and shoulder associated with posture and muscular activity have been determined, which can be used for the prevention of musculoskeletal pathologies. In addition, the knowledge what was gathered from the real environment of the operating theater can be useful for training of surgeons in laparoscopic surgery on adaptation of the posture during the intervention. Finally, it is relevant to highlight the whole research process conducted for more than a decade, starting from the initial epidemiological study and evolving with the use of biomechanics methodology up to the analysis of neuromuscular control strategies using the uncontrolled manifold hypothesis model.

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