International Journal of Medical, Medicine and Health Sciences
ISSN: 2517-9969
Vol:10, No:5, 2016

An Ergonomic Handle Design for Instruments in Laparoscopic Surgery

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Abstract**—**In this paper, the design and evaluation of a handle for laparoscopic surgery is presented. The design of the handle is based on ergonomic principles and tries to avoid awkward postures for surgeons. The handle combines the so-called power-grip and accurate-grip in order to provide strength and accuracy in the performance of surgery. The handle is tested using both objective and subjective approaches. The objective approach uses motion capture techniques to obtain the angles of forearm, arm, wrist and hand. The muscular effort is obtained with electromyography electrodes. On the other hand, a subjective survey has been carried out using questionnaires. Results confirm that the handle is preferred by the majority of the surgeons.

Keywords**—**Laparoscopic Surgery, Ergonomics, Mechanical Design, Biomechanics.

I. Introduction

THE expansion of laparoscopy or Minimally Invasive Surgery (MIS) during the last twenty years is due to the proven benefits that this type of interventions provides to the patients. Patients need less recovery time and the risk of infection and post-surgery pain is reduced. Furthermore, it also has aesthetic benefits for the patient, reducing the size and length of scars. In contrast, surgeons suffer due to the poor ergonomic characteristics of their workplace [1]-[3]. Indeed, the main characteristic of laparoscopic surgery is that the surgeon uses special surgical instruments through small incisions in the patient. This situation reduces the space available for the interventions and limits the degrees of freedom of the surgeons [4]. One of the main ergonomic problems associated with MIS is that surgeons have to adopt awkward postures during surgical interventions [5]. This fact is especially important in the arms, wrists and hands of the surgeons. Some studies reveal that the way in which the surgeon holds the instruments is among the main causes of discomfort [6]-[9]. The prime consequence of using laparoscopic instruments is the physical fatigue that they can originate in the surgeons and the risk for the patient when this happens [10]-[12]. However, the poor ergonomic characteristics have another important consequence in the long term, namely the emergence of musculoskeletal disorders (MSDs) in surgeons [13], [14]. In fact, in the last years MSDs have affected experienced surgeons more and more and there is scientific evidence that as they get older the problem is accentuated. In the last six years several articles have highlighted this problem indicating that this is a problem which is increasing with time [15]-[17].

Several researchers have proposed different ergonomic design of handles. For instance, a rocker handle was proposed by [18] in order to reduce the velocity of the elbow and shoulder. A handle with a rotating ring for the thumb was proposed to reduce awkward positions of the hand [19]. Many of the solutions proposed in the literature try to avoid the hyperflexion of the wrist [20]-[22]. It is demonstrated that the ring-handle type causes a great hyperflexion of the wrist and obliges the surgeon to maintain this posture. However, a pistol handle-type reduces the hyperflexion enabling the hand to adopt a more neutral position.

The assessment of the ergonomic characteristics of the handles is an important issue that has not been sufficiently studied in MIS. In fact, there are several methods for the ergonomic evaluation of the workplace which are based on validated questionnaires. Examples of these methods are the following: Norm ISO 1122 [23], Rapid Entire Body Assessment (REBA) [24] and Rapid Upper Limb Assessment [25]. These methods are general methods which can be used for light manual work. However, laparoscopic surgery requires a more specific method providing a more accurate evaluation of the wrist and forearms. Experimental studies about the ergonomic evaluation of surgical theaters have been carried out by several authors [25]-[27]. For instance, in [28] the experimental evaluation is done using a simulated abdomen, or in [9] and [29] different tasks are proposed to assess the ergonomic properties of a new handle.

The main objective of this work is to present a new handle design for laparoscopic surgery which has been developed using ergonomic principles. The handle reduces the hyperflexion of the wrist and avoids local contact zones between the hand and the handle. The methodology and results of the experimental evaluation of the ergonomic

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characteristics are presented. The results of the experiment provided new ideas about how to improve the ergonomic characteristics of the handle. These ideas have been used in the redesign of the original idea and the modifications are presented in a new prototype.

II. Design of the New Handle

A. Design Constraints

Fig. 1 shows the scheme of a laparoscopic instrument. This kind of tool can be divided into two parts. The endoscopic part works inside the patient and is formed by the shaft and the end-effector. The end-effector can be a grasper, scissors or dissector. The external part of the instrument works outside the patient. As is shown in Fig. 1, it mainly consists of the handle which contains the elements for the activation of the end-effector. The shaft is the element which connects the handle with the end-effector. It needs to be long enough to reach and manipulate the organs of the patients. The instrument accesses the patient through small incisions in the abdominal wall. A trocar is placed in the incision to avoid the direct contact between the shaft and abdominal wall. Considering these characteristics, the degrees of freedom of the instruments are the five Φ angles indicated in Fig. 1. They are the following: The rotation around the main axis of the instrument, i.e. Φ_1, the rotations around the trocar, i.e. Φ_2 and Φ_3, the translation along the trocar, i.e. Φ_4, and the opening and closing motion of the end-effector shown in Fig. 1 as the angle α. The handle needs to contain the elements for the activation of the rotation Φ_1, and the opening motion of the grasper. Traditionally ring-handles are used to open and close the grasper whereas a rotation wheel is used to provide the Φ_1 motion.

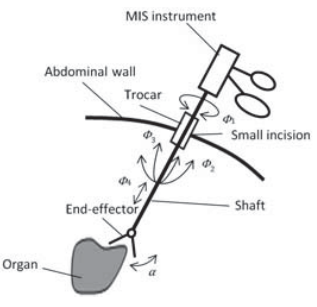

Fig. 1 Scheme of the surgical instrument

B. Ergonomic Principles and Requirements

It is obvious that the design of a handle is always conditioned by the human hand grip. However, the human hand has a multitude of possible ways of gripping a handle. We can say that a grip requires the adaptation of the hand to the handle together with the capacity to exert a force to manipulate an object. Ergonomic principles divide the grips of the handles into two types. They are the power and precision grips [30]. The power grip is the way in which a tool is handled when is necessary to apply a great force or it needs to be held firmly. Examples of power grips are the handle of a hammer or an axe, where the handle has circular shape and the hand and fingers are closed around the handle. On the other hand, the precision grip is used when it is necessary to manipulate an object accurately. Examples of the precision grip are the way in which a pen is held or the way in which tweezers are used. In the power grip the whole hand has an important role whereas in the precision grip the index finger and thumb are the parts of the hand touching the handle.

In the case of surgical instruments both the power and precision grips are necessary. The power grip allows the surgeon to grasp the handle firmly and to apply the necessary force when required (e.g. suturing tissues or organs). The precision grip is necessary to manipulate the organs, needles, etc. with accuracy.

Based on the aforementioned characteristic the pistol handle-type seems to be the most adequate for this kind of application. Fig. 2 shows the first designs proposed in this work where the handle consists of two parts. The power grip part is formed by a cylinder which is griped with middle, ring and little fingers whereas the precision part is designed to be gripped with the index finger and thumb. These fingers are also used to activate the tools providing the opening and closing motions (i.e. α angle) of the end-effector. This design allows the hand to grip the handle completely. In other words, there are no small zones of contact between the hand and the handle that make the handle uncomfortable.

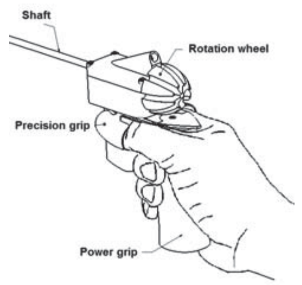

Fig. 2 First design of the handle based on ergonomic principles

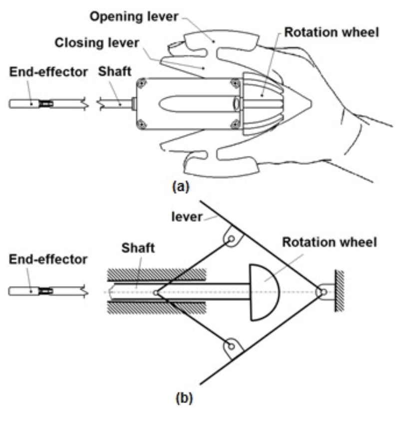

Fig. 3 Opening and closing activation: (a) Hand position and (b) kinematic scheme

C. Kinematic Design

In order to open and close the end-effector two levers are placed on both sides of the instrument. They are activated using the index finger and thumb as is shown in Fig. 3 (a). When the surgeon opens the fingers the mechanism inside the instrument transmits the motion to the end-effector opening the grasper. The mechanism is formed by two links which connect the levers with the shaft as is shown in Fig. 3 (b). When the surgeon closes the fingers, the grasper closes as well. The levers have a surface surrounding the fingers in order to allow the motion in both directions.

The rotation of the end-effector around the main axis of the instrument is activated with the thumb as is shown in Fig. 4. The rotation wheel transmits the motion directly to the shaft and the end-effector as is shown in the kinematic scheme in Fig. 3 (b). This system allows the modification of the orientation in which the organs or tissues can be grasped.

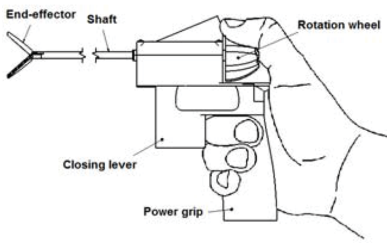

Fig. 4 Activation of the rotation of the shaft with the thumb

D. Ergonomic simulation

In order to obtain the ergonomic dimensions of the handle a hand model was created using Autodesk Inventor™. This model has sixteen degrees of freedom and is illustrated in Fig. 5 (a). The degrees of freedom correspond to the motion of the fingers. The model was built using 3D prototyping to verify the natural behavior of the hand (see Fig. 5 (b)). Once the hand model was checked the simulation of the hand-handle provided the correct dimensions of surfaces, levers and the rotation wheel (see Fig. 5 (c)).

E. Prototype construction

In order to test the new handle a functional prototype was built using 3D prototyping. Fig. 6 shows this plastic prototype. Only the handle has been prototyped and the shaft and end-effector have been taken from other commercial instruments. Thus, the differences obtained from the results of the ergonomic tests are only due to the ergonomic configuration of the handles.

III. Evaluation

A. The Test Design

An experimental evaluation of the ergonomic characteristics of the handle has been carried out in the Ergonomic and Usability laboratory of Valdecilla Virtual Hospital, in Santander, Spain. In the survey two different handles were compared. The instruments selected for the experiment are two 5-mm dissectors. The handle was compared with a Covidien™ commercial ring-handle type, which is a very common handle used in laparoscopic surgery. In the experiment several volunteers performed a number of surgical tasks with the two instruments. Afterwards, data processing provided information about the ergonomic characteristics of the two handles.

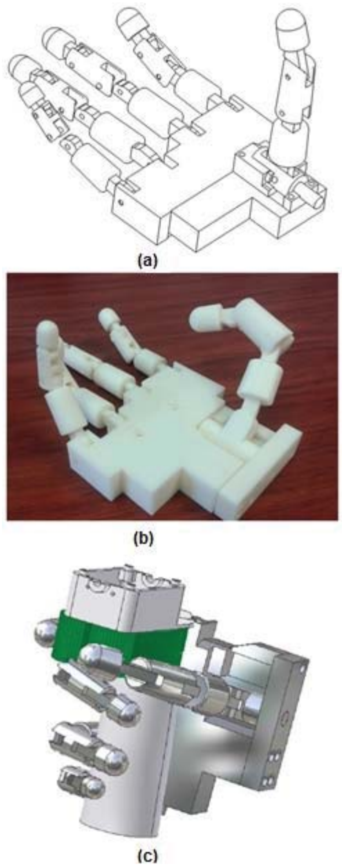

Fig. 5 Hand model for the ergonomic design of the handle: (a) virtual model, (b) 3D prototype and (c) simulation

B. Volunteers and Independent Variables

In order to avoid the influence of previous use of ring-handle instruments, twelve volunteers were selected without surgical experience. Independent variables obtained from volunteers included age, sex, hand size, muscular strength, weight and height. All of them were right-handed people in order to avoid the influence of the predominant use of the left hand. The participants expressed that they did not have any injuries or musculoskeletal disorders. All participants signed the informed consent form.

C. The Tasks

Each volunteer had to perform three tasks with the two handles working in endotrainers (see Fig. 7). Actual operations were not considered because of the lack of repeatability and the risk for patients. The order of use of the instruments was randomly selected to avoid the learning effect. The first task consists of three metal rings located at the

International Journal of Medical, Medicine and Health Sciences
ISSN: 2517-9969
Vol:10, No:5, 2016

top of three blocks. The volunteer had to take a needle with the dissector and pass it through the rings. In the second task the volunteer had to loop a string around a cylinder.

Fig. 6 Prototype of the surgical instrument

The last task consisted of a flat board drilled with six figures. The volunteer had to place numbers and letters in the corresponding grooves.

D. Data Collection

Dependent variables are those obtained when the experiment is finished. In this survey two types of variables are considered: subjective and objective ones. Subjective variables are obtained after the test from the opinions of the volunteers about the ergonomic characteristics of the new handle in comparison with the commercial one. Questionnaires were used for the subjective analysis whereas biomechanical variables were obtained for the objective one. Two kinds of biomechanical variables were obtained. The first one was the motion of the forearm, wrist and hand using goniometry. The muscular effort was also measured using superficial electromyography (sEMG).

The questionnaire formulated three questions for the participants. These questions had to be answered after each task with the two surgical instruments. In the first one the participant has to rank the degree of difficulty to perform the task (Q1). In the second one the subject reports which one of the two handles caused more pain (Q2), ranked on a scale from 0 to 10. In the last question the participant is asked to choose the best instrument following their own criteria (Q3).

The goniometry measured the flexion and extension of the wrist (G1), the radial and ulnar deviation (G2), the pronation and supination of the forearm (G3) and shoulder abduction and adduction (G4). Electromyography electrodes were placed to measure muscular activity of thenar muscle (EMG1), flexor digitorum superficialis (EMG2), extensor digitorum communis (EMG3) and trapezius pars decendens (EMG4). The root mean square values were used to quantify the intensity of the muscular activity with respect to the maximum voluntary contraction (MVC).

IV. Results and Design Modifications

A. Results of the Tests

The answers to the questionnaire have generated the statistical results with the opinion of the volunteers about the degree of difficulty in completing the different tasks using both instruments. These statistical results are shown in Table I.

Fig. 7 Experimental evaluation of the handle

The results about the difficulty of the tasks were similar with the two handles. The first row of Table I shows mean and Standard Deviation (SD) for the two handles. The difficulty was slightly lower with the new handle but this difference cannot be considered significant. The pain referred by the participants were higher with the commercial handle and this difference was significant. As is shown in the third row of Table I, a total of 67% of the volunteers preferred the new handle. The overall results show that the opinion of the volunteers when using the new handle is significant better than when using the commercial one. The results are similar in the different tasks when it is analyzed individually.

TABLE I
Results from Questionnaires

Muscular Group	Prototype	Ring-handle type
Q1 - Mean (SD)	5.1 (1.92)	5.8 (2.03)
Q2 - Mean (SD)	3.8 (1.13)	5.3 (1.83)
Q3 - (%)	66.9	33.1

The goniometric study is also favorable to the new handle. Indeed, Table II shows the results of this analysis. The flexion and extension of the wrist is about half of the value of the commercial handle. Furthermore, the new handle produces a slightly extension of the wrist while the commercial one produces a strong flexion. This is a undeniable advantage for the new handle. The values of the radial and ulnar deviation, the pronation and supination of the forearm are higher for the new handle. However, this angles are within the acceptable values given by the ergonomic procedures in the literature [23], [24], [25]. Finally, the shoulder abduction and adduction is similar with the two handles.

TABLE II
Results from the Goniometric Angles

Muscular Group	Prototype Mean (SD) - deg	Ring-handle type Mean (SD) - deg
G1	-12.2 (4.33)	25.1 (6.65)
G2	-13.4 (5.55)	-4.3 (8.66)
G3	46.5 (9.87)	-3.2 (7.88)
G4	30.7 (6.21)	29.1 (5.87)

Table III shows the results obtained for the measurement of the muscular effort. There are not significant differences between the muscular effort required by the new handle and the commercial one. The Thenar muscle was used in a similar way as is shown in the first row of Table III. Flexor digitorum surperficiales requires lower effort with the new handle but this difference cannot be considered significant. Extensor digitorum communis required more effort with the new handle but again the difference is not significant.

TABLE III
RESULTS FROM THE EMG MEASUREMENTS

Muscular Group	Prototype Mean (SD)	Ring-handle type Mean (SD)
EMG1	46.1 (31.92)	45.2 (22.91)
EMG2	39.3 (19.13)	42.3 (19.23)
EMG3	28.9 (12.22)	22.2 (16.78)
EMG4	28.7 (12.34)	30.2 (19.22)

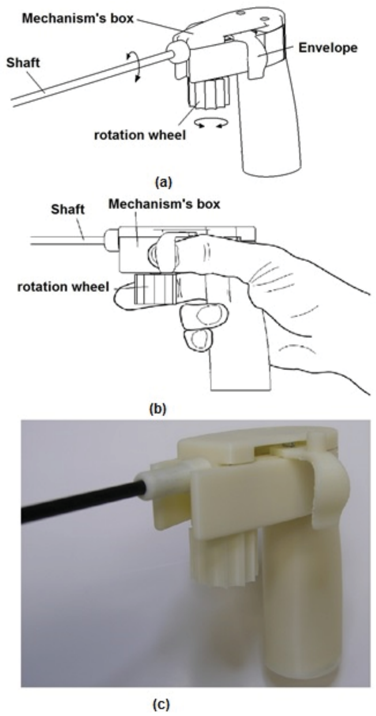

Fig. 8 Redesign of the surgical instrument

B. Redesign of the Handle

One of the main drawbacks expressed by the volunteers is the size of the transmission mechanism box. However, the main complaint is relative to the rotation of the end-effector around the main axis of the instrument. The volunteers expressed the difficulties that they had when tried to activate this motion. The rotation wheel is not easily activated with the thumb. Furthermore, when this wheel needs to be activated the participant cannot maintain the force closing the end-effector. They suggested that the wheel could be placed behind the mechanism's box in order to be activated with the middle finger without using any of the other fingers used to close the grasper. Another improvement suggested by the volunteers was to modify the outer surface of the levers. The envelope surfaces are uncomfortable because of the lack of adaptation to the fingers motion.

The handle has been redesigned based on the results obtained from the test. The transmission mechanism has been reduced in size and weight and located between the levers as is shown in Fig. 8 (a). In this way the instrument is more compact and manageable. The rotation wheel has been located behind the box of the transmission mechanism in order to be activated with the middle finger instead of using the thumb, as is shown in Fig. 8 (b). In this way the thumb and index finger remain always on the levers. In the new design the outer surfaces of the levers are adaptive and can be modified depending on the size of the hand and fingers. Fig. 8 (c) shows the new prototype that has been built and tested.

V. CONCLUSIONS

In this paper the design of a new ergonomic handle for laparoscopic surgery has been presented. The design of the handle has been carried out using ergonomic principles in order to obtain the so-called power grip and precision grip. A 3D prototype of the handle has been tested in order verify its ergonomic characteristics. A survey has been carried out to evaluate the features. The design of the experiment for the comparison of the new handle with another commercial instrument is described in the paper. Questionnaires are used to obtain the opinion of the volunteers who performed the tests. The answers of the participants provided the subjective assessment of the handle. Biomechanical variables are obtained during the performance of the tests in order to have objective information about motion of the forearm and muscular activity of the participants.

The results show that the pistol handle significantly reduces the hyperflexion of the wrist. The ring-handle type forces the user to bend the wrist in a posture that goes beyond the limits of comfort. Furthermore, the shape of the handle provides a comfortable posture of the hand avoiding high-pressure zones. This fact reduces the pain that the users suffer when they have to apply force to grasp the organs.

ACKNOWLEDGMENT

This paper has been developed in the framework of the Project DPI2010 funded by the Spanish Ministry of Economy and Competitiveness.

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