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# A Method to Assess Upper-Body Postural Variability in Laparoscopic Surgery*

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*Abstract*— **Quantitative analysis of surgeons' motor variability during the surgical practice is still scarce. Therefore, a framework for the analysis of surgeon upper-body postural variability during laparoscopic procedures was developed. 3D kinematics analysis gave us information regarding the head posture adopted by the surgeons with respect to the trunk and how this varies during surgical training activities. Furthermore, surgeon's upper-body joint variability was quantified using the framework of the Uncontrolled Manifold hypothesis, allowing to separate the combination of joint angles that were equally able to stabilize head mean posture on sagittal plane for those solutions that were destabilized head mean posture. The results showed that the underlying framework was able to quantify surgeons' motor variability, providing inspiration for new human-machine interaction designs, as well as more targeted ergonomics assessments.**

## I. INTRODUCTION

Musculoskeletal Disorders (MSD) is not a diagnosis, but stand as an umbrella term covering a broad range of inflammatory and degenerative disorders of the locomotor system that develop as a result of repetitive movements, awkward postures, sustained force and other risk factors [1]. Work-related musculoskeletal disorders (WRMSD), by definition, are a subset of MSD that arise out of occupational exposures [2]. They affect both women and men and all sectors of activity and are a major financial cost to businesses and society at large [3]. Surgeons who perform laparoscopy are concerned as a high risk occupational group for developing WRMSD as a direct consequence of the postures that they often have to adopt during operation, the poor ergonomic design of the workplace and instruments, and because of their low awareness about ergonomic recommendations in general [4-8].

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The reduction of the risk to suffer WRMSD can be achieved by the design (or redesign) of the workspace by taking into account the physical limitations and capabilities of the surgeons. Back to the 30's, Bernstein [9] (cited in [10]) had defined this procedure of ergonomic intervention as the *normalization* of the work process–i.e., the ratio of job's demands to worker's performance capability. Nowadays, an important step for optimizing the man-machine interface in laparoscopic surgical processes is to characterize the surgeons' functional capabilities and limitations in relation with the work demands [11]. This is determined by assessing surgeon's neuromusculoskeletal and sensorimotor performance limits. Any mismatch may leads to WRMSD [12]. This biomechanical approach is the fundamental part of physical ergonomics and workspace design, as it has an explicit hypothesis of injury mechanism linked to it. Bernstein [9], had also included in his ergonomic framework the *biomechanical rationalization* of operations (i.e., the organization of a work-task according to biomechanical principles in order to increase efficiency), however, based on the degrees of freedom (DOF) problem rather on the scientific management approach (e.g., Taylorism) [13], that was consisting in identifying a "physiologically feasible motor complex solution in order to achieve a goal with minimal effort and discomfort of the part of the worker" [9]. Nowadays, the characterization of the surgeon motor variability and the underlying surgical performance could provide inspiration for new man-machine interaction designs, as well as more targeted training methods [14] or ergonomics assessement [16].

The motor redundancy as a result of the numerous DOF of the human locomotor apparatus compared with the substantially lower anatomical constraints that are imposed by the structure of the musculoskeletal system at joints' level, gives to the surgeons the possibility to adopt an infinite number of postures during the surgery tasks and consequently the ability to execute a countless voluntary motor patterns in order to accomplish their activities. A coordinate motor pattern can be viewed as a purposeful pattern of actions by a set of elemental variables which are characterized by a certain irreducible level of motor variability in their outputs [15].

Motor variability exist in every voluntary movement. At the kinematic level, coordination refers to the behavior of the spatiotemporal relationship among body segments. However, not all of the possible postures that surgeons can adopt are healthy or purposeful. Given the constraints imposed by i) anthropometric characteristics, ii) the natural limits of sensorimotor system capabilities, iii) workplace configuration, iv) man-machine interaction and v) the required performance of the intended operation, a *motor strategy* is required that enables to define a systematic relationship between working demands and the adopted working posture by the surgeon [16]. The biomechanical rationalization, therefore, is linked with the motor control process of voluntary movements and how it is influenced by workspace or task design.

For the workplace layout of the operation theater, the ability of the central nervous system (CNS) to organize the abundant DOF of the locomotor apparatus into purposeful actions has to be taken into account. The uncontrolled manifold hypothesis (UCM) allows for the quantification of the overall kinematic variability that is observed when a posture is sustained, into the task-relevant and the the task-irrelevant component. According to the principle of motor abundance, there are a combination of solutions that are equally able to solve the motor task problem within an acceptable margin of error [15, 17]. This combination of skilled solutions is reflected in the "good" variability ($V_{UCM}$) of the motor patterns when the same task is repeated. On the other hand, covariation patterns of the elemental variables that affect important characteristics of the performance variable and are irrelevant of the ongoing task are tried to be limited by the controller as they are reflected "bad" variability ($V_{ORT}$).

Therefore, motor-variability can be regarded as an intrinsic feature of the established motor synergies which corresponds to the error compensation of their elements and to the flexibility feature that they possess. This means that neuromotor variability possesses *structure*, and its analysis can gain important information regarding the complex behavior of the human motor system. In this sense, the main goal of a synergy is to try to make most variability "good" ($V_{UCM}$). Hence, the analysis of the motor variability can be used to gain insight into the way synergies are structured and what action they are trying to accomplish [15]. In this regard, the purpose of this study was to assess the posture of the head with respect to the trunk and the upper-limb joint configurations that do and do not affect the head posture.

## II. METHODS

### A. Participants

Thirteen surgeons with an average age of 41 years (range 31-58 years) and different levels of laparoscopic experience participated in the study while they were attending a laparoscopic training course. During the course, the participants performed several laparoscopic training activities with the support of experienced surgeons and the assistant staff. Every surgeon had to perform each training activity for a minimum of 1 hour on a given training model. This training model consisted of a box trainer for the basic laparoscopic tasks and an animal model for advanced procedures. All measurements were recorded within the operating room. The height of the operating table and its distance from the surgeon was adjusted according to the surgeon needs. The monitor was placed on a wheel cart; free to move around the operating room according to the subject needs, and its height (highest part of the monitor) was fixed at 108.5 cm from the floor.

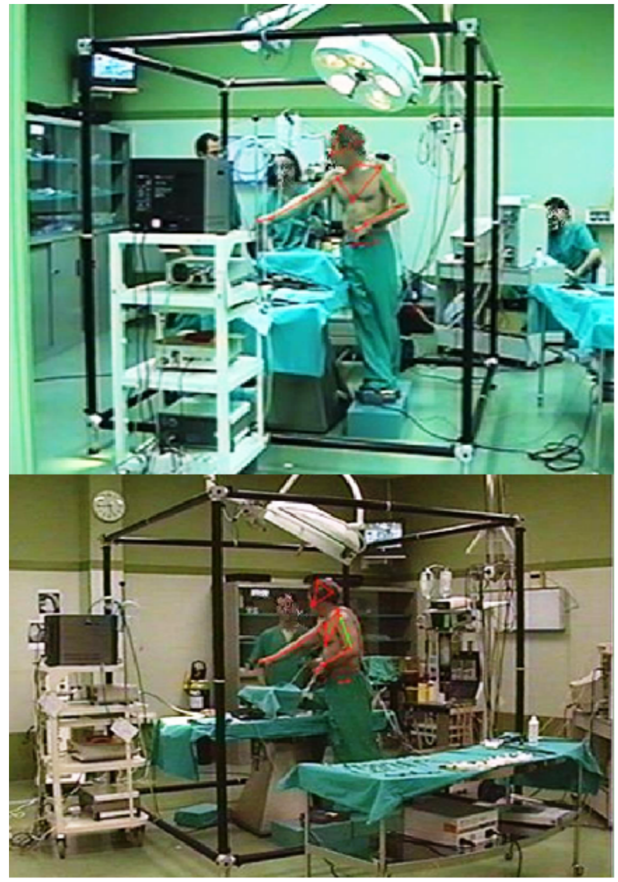

Fig. 1. Experimental set up showing a subject at the operation theater and the mechanical model that was used in the study

### B. Kinematic Data

Two S-VHS video cameras (Panasonic AG-DP800H, AG-DP200E) with a sampling rate of 50 Hz were used to record the surgeon's posture during each laparoscopic activity and from different points of view. The recorded videos were processed using the package Kinescan/IBV (IBV, Valencia, Spain) obtaining the three-dimensional (3D) coordinates of the markers that define the mechanical model associated to the surgeon (Fig. 1).

This mechanical model is defined by 8 anatomical points manually digitized: Nose, Cranial Vertex, Occipital, Xiphoid, Left Shoulder (LS), Right Shoulder (RS), Left Hip (LH) and Right Hip (RH). 3D coordinates of the cited points were obtained using the algorithm known as DLT (Direct Linear Transformation) [18]. Head and Trunk segments were defined as solids and their position and orientation were obtained by means of a local systems of reference (LSR) fixed to them. This process allows for the measurement of the head posture adopted by surgeons, as well as the computation of its position and orientation with respect to the trunk (Fig. 2).

The mechanical model associated to the trunk ($X_t$ $Y_t$ $Z_t$)

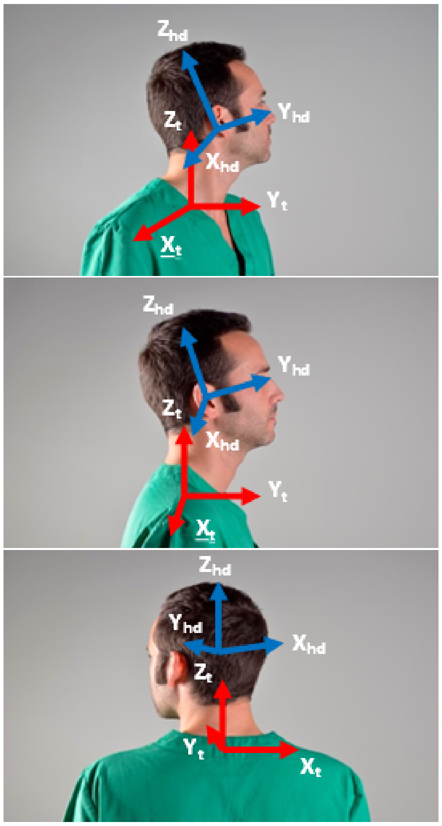


Fig. 2. Graphic representation of the joint coordinate system (JCS). Angles of the head are showed with respect to surgeon's trunk. In lateral inclination movements (above), negative values indicate tilt to right side and positive values tilt to the left side of the head. In flexion/extension movements (middle), negative values mean flexion of the head and positive values extension of the head. In axial rotations (bottom), positive values indicate right rotations and negative values rotations to the left.

has its origin ($O_t$) at the midpoint of RS-LS and it is defined by means of the RS, LS, LH, RH and the Xiphoid markers. The directions of the axes for this model are defined as follows:

1) the direction of the ($X_t$) axis is perpendicular to the plane formed by the midpoint of RS-LS, the midpoint of RH-LH and the Xiphoid markers
2) the direction of the ($Z_t$) axis is the opposite one to the vector connecting the midpoint of RS and LS and the midpoint of RH and LH
3) the direction of the ($Y_t$) axis is perpendicular to the plane formed by $Z_t$ and $X_t$ axes

The mechanical model associated to the head ($X_{hd}$ $Y_{hd}$ $Z_{hd}$) has its origin ($O_{hd}$) at the midpoint of Nose and Occipital and it is defined by means of the Nose, Vertex and Occipital markers. The directions of the axes for this model are defined as follows:

1) the direction of the ($X_{hd}$) axis is perpendicular to the plane formed by Vertex, midpoint of Occipital and Nose markers
2) the direction of the ($Z_{hd}$) axis is the vector connecting and the midpoint of Occipital and Nose and Vertex
3) the direction of the ($Y_{hd}$) axis is perpendicular to the plane formed by the $X_{hd}$ and $Z_{hd}$ axes

The posture of the head was defined with respect to the trunk, considering posture as the position and orientation of body segments. The next step is to define the surgeons resultant posture using purposeful clinical combinations of flexion-extension, internal-external rotation and lateral inclination of body segments. A joint coordinate systems is used to obtain the posture of the head with respect to the trunk:

1) $1^{st}$ rotation with respect to the $X_t$ axis, where head flexion-extension takes place
2) $2^{nd}$ rotation with respect to the floating axis (defined as the cross product of the $X_t$ and $Z_{hd}$ axes), where lateral inclination takes place
3) $3^{rd}$ rotation with respect to the $Z_{hd}$ axis, where axial rotation takes place

### C. Missing Data

Due to the training character the operation process was not continued. Sometimes, surgeons were receiving instructions and advices from their trainers and/or the had to change the laparoscopic instruments, so that they instantly had to stop their practice. Thus, the records corresponding to these idle times were not considered for analysis. Additionally, surgeon's postures that could not be identified because of occlusions were also excluded.

### D. Error Analysis

The data obtained after kinematic analysis gave us information regarding the head posture and how this varies during the surgical training activities. Since no smoothing method was used, the random error introduced in the kinematic parameters was the result of the accuracy of manual digitalization of anatomical points. Thus, to determine the degree of reliability of the model it is necessary to estimate the errors due to the propagation through the algorithms used. A frame was digitized with a scene filmed 334 times for a subject. All the kinematic parameters were computed by means of the developed mathematical algorithms, and therefore the mean, standard deviation and standard error of each parameter were estimated. The random error can be estimated from these parameters through the equation

$$\bar{X} - t_{0.01}(334)\frac{s_x}{\sqrt{N}} \leq X \leq \bar{X} + t_{0.01}(334)\frac{s_x}{\sqrt{N}} \leftrightarrow$$
$$\bar{X} - 2.58\frac{s_x}{\sqrt{334}} \leq X \leq +2.58\frac{s_x}{\sqrt{334}}$$

The deviation from zero, which is the expected value, can be estimated for each computed measurement. This deviation refers to the arithmetic average of the range of variation of each parameter obtained during the study. Therefore, the relative error related to the kinematic parameters can be estimated.

### E. Uncontrolled Manifold Hypothesis

A forward kinematic model that links the joint configuration of the upper-body with the controlled variable (head)


Fig. 3. Schematic representation of the segmental angles computed in the sagittal plane

was developed (Fig. 3). The geometric model representing the head posture along the sagittal plane is

$$X_{\mathrm{hd}} = \begin{bmatrix}\cos\alpha_{\mathrm{f}} & \cos\alpha_{\mathrm{u}} & \cos\alpha_{\mathrm{n}}\end{bmatrix}\begin{bmatrix}\mathrm{l_f}\\ \mathrm{l_u}\\ \mathrm{l_n}\end{bmatrix} \tag{1}$$

where $\alpha_{\mathrm{f}} = \theta_1$, $\alpha_{\mathrm{u}} = \theta_1 + \theta_2$ and $\alpha_{\mathrm{n}} = \theta_1 + \theta_2 + \theta_3$ with

- $\theta_1$ - is the angle formed between the longitudinal axis of the forearm and the horizontal
- $\theta_2$ - is the angle formed between the longitudinal axis of the forearm and the longitudinal axis of the upper-arm
- $\theta_3$ - is the angle formed between the longitudinal axis of the upper-arm and the longitudinal axis of head

The mean joint configuration across trials ($\Theta_0$) was computed for each subject and the deviation of each particular $i$-trial ($\Theta_i$) from the mean joint configuration was computed

$$\Delta\Theta = \Theta_0 - \Theta_i \tag{2}$$

The uncontrolled manifold was approximated linearly by the null space of the Jacobian matrix based on the mean joint configuration. The linearized forward kinematics around the mean joint configuration $\Theta_0$ is

$$r_i - r_0 = J(\Theta_0)\cdot\Delta\Theta \tag{3}$$

where $r_0$ is the value of the controlled variable for the mean joint configuration and $r_i$ its value at the $i$-trial. The Jacobian $J$ is a matrix of partial derivatives that correspond to changes in the task-level variable with respect to each of the segmental angles. The null space of the Jacobian, $J$, was computed to provide basis vectors, $\varepsilon_i$, spanning the linearized UCM. The joint space is three-dimensional ($n = 3$), and for the one-dimensional task variable ($d = 1$) the null space is two-dimensional ($n - d = 2$). The two basis vectors $\varepsilon_1$ and $\varepsilon_2$ defining the null space were computed with the *nullspace* function of the package **pracma** in R environment. The component of the deviation matrix $\Delta\Theta$ which is parallel to the UCM represents how much deviation occurs without altering the value of the task-level variable and was obtained by its projection onto the null space ($\Theta_{UCM}$). To compute the orthogonal projection of the $\Delta\Theta$ the projection matrix $Q$ for a the two-dimensional null space of $R^3$ spanned by the vectors $\varepsilon_1$ and $\varepsilon_2$ was computed

$$Q = A(A^TA)^{-1}A^T \tag{4}$$

therefore

$$\Theta_{UCM} = Q\Delta\Theta^T \tag{5}$$

The component perpendicular to the null space is

$$\Theta_{ORT} = (I - Q)\Delta\Theta^T \tag{6}$$

where $I$ is the identity matrix. The amount of variability per degree of freedom within the uncontrolled manifold is

$$V_{UCM} = \sqrt{(n-d)^{-1}N_{Trials}^{-1}\sum\Theta_{UCM}^2} \tag{7}$$

The amount of variability per degree of freedom perpendicular to the uncontrolled manifold is

$$V_{ORT} = \sqrt{d^{-1}N_{Trials}^{-1}\sum\Theta_{ORT}^2}. \tag{8}$$

## III. Results and Discussion

The propagation of the random errors into the kinematic parameters were computed (Table 1 and 2).

TABLE I

Maximum standard error of 3D coordinates ($P$=0.01)

| | Marker | | | |
|---|---|---|---|---|
| | *Nose* | *Occipital* | *Vertex* | *Xiphoid* |
| **Coordinate X** | 0.04% | 0.09% | 0.08% | 0.05% |
| **Coordinate Y** | 0.04% | 0.07% | 0.06% | 0.07% |
| **Coordinate Z** | 0.04% | 0.05% | 0.07% | 0.1% |
| | *LS* | *RS* | *LH* | *RH* |
| **Coordinate X** | 0.06% | 0.11% | 0.04% | 0.09% |
| **Coordinate Y** | 0.09% | 0.09% | 0.07% | 0.04% |
| **Coordinate Z** | 0.07% | 0.13% | 0.007% | 0.08% |

TABLE II

Maximum standard error of 3D angles ($P$=0.01)

| | *Flexion-Extension* | *Inclination* | *Rotation* |
|---|---|---|---|
| **Head-Trunk** | 11.10% | 2.30% | 5.22% |

The results of the 3D kinematics for the head's posture with respect to the trunk show that for the 86% of the surgeons the flexion-extension angle's range was less than 20° (mean range: 13.83° ± 3.25°; mean flexion: 2.8° ±

2.6°e; mean extension: 14.76° ± 9.86°) and for the 86% of them the left-right inclination range was less than 15° (mean range: 10.58° ± 2.53°; mean left inclination: 4.75° ± 4.09°; mean right inclination: 10.71° ± 6.17°). The range of the axial rotation of the head with respect to the trunk was, in general, high (mean range: 33.82° ± 20.15°; mean right rotation: 14.21° ± 12.18°; mean left rotation: 9.31° ± 7.17°) with four surgeons exhibited an average extension angle $> 20°$. In 4.5% of the obtained data subjects had the head flexed and in 10% left tilted. It seems that the surgeons' head posture depends on the orientation of the monitor at the operation theater, as has been reported in other studies [19, 20], and on the surgeon's trunk posture during the performance of the laparoscopic activity. Therefore, when the surgeon is placed on the sides of the operating table, he/she needs to rotate and bend the trunk in order to manipulate the surgical instruments with the hands. Lateral inclination of the trunk is compensated with opposite lateral inclination of the head [21]. The extended, tilted to the right and with a high axial rotation range posture of the head during operation was mentioned also in other studies [21, 22].

Our results showed that surgeons maintained their head rather static in the flexion/extension movements throught intervention procedures. The goal of the UCM analysis was to test whether upper-limbs variability stabilized or destabilized head posture on the sagittal plane, that corresponds to the flexion/extension plane. Although the inter-trial variability in joint configuration space should be structured in a manner to stabilise manual operation-task movements, by definition it could be structured also in a manner to stabilize other important controlled-variables as well. The head movement in the anterior-posterior direction is a plausible candidate as it is related with postural stability. Moreover, head posture is constrained by the displacement of the monitor. The ratio between $V_{UCM}/V_{ORT}$ indicated that surgeons stabilized head movements in the anterior-posterior direction by the co-variation of the upper-limb joint angles (Fig. 4). Although a formal statistical comparison cannot be obtained due to the no-standardized actions among surgeons, individually, it can be suggested that there is an evidence that upper-limbs joints co-varied realizing purposeful movements in order to stabilize head posture.

A similar framework was presented by Nisky et al. [14], but in this case focused on robotic surgery. Although robotic surgery needs for specific surgical skills due to the introduction of a robotic interface and other additional factors, this work was one of the first to apply motor control techniques to the analysis of the surgeons posture. They opened a novel research field, which seeks to improve the surgeons performance and the current training programs. Maybe in a near future this UMC could define the surgeons level of experience, distinguishing experts from novices, or to design workspace layout taking into consideration its effect to individual motor performance.

A markerless analysis using the developed 3D mechanical model allowed us to characterize surgeons posture while they were performing laparoscopic activities in the OR. Besides,

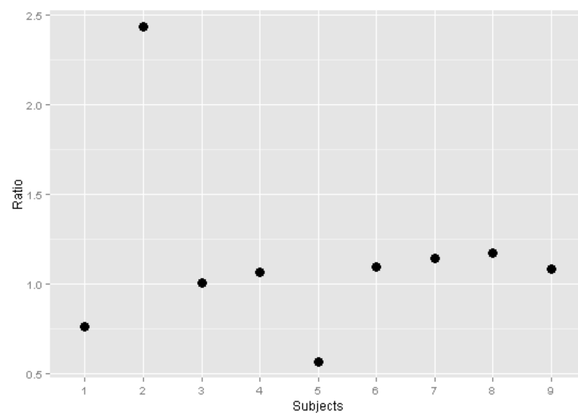


Fig. 4. Ratio between $V_{UCM}/V_{ORT}$ for each subject.

the 3D mechanical model provided an accurate and non-intrusive way to record the kinematic parameters of the surgeons movements. Motor control analysis is an novel research line in laparoscopic surgery, and therefore further studies are needed to reinforce these findings.


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