Standard Deviation from the Average Cutting Velocity as a Criterion for Comparing Robot Trajectories and Manual Movements of a Doctor for Performing Surgical Operations in Maxillofacial Surgery

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***Abstract* — This article presents experimental studies comparing the trajectories obtained from the movements of a medical instrument by a surgeon and the robot KUKA LWR4 +. The comparison is made according to one of the four main criteria: standard deviation derived from the average cutting velocity. Such metrological studies are a method of justifying the expediency of using a robot for medical operations. This criterion can be used to compare the trajectories when performing medical operations in maxillofacial surgery using a diode laser. The presented comparison criterion is based on the ISO 9283 standard. In addition to the main criterion, there are two additional ones. The trajectories for comparison were obtained by scanning the movements of a medical instrument using a coordinate measuring machine, namely, the laser tracker LTD800. By using a robot, it is possible to achieve higher accuracy of trajectories by the velocity of the movement of medical instruments in comparison with that of a surgeon.**

***Index Terms* — medical robotics, human–machine cooperative system, surgical assistants, laser tracker, trajectory evaluation, accuracy, diode laser**

I. Introduction

The use of laser technologies for performing maxillofacial operations has recently become a topical direction in medicine. For example, the use of a diode laser with an impulse pump driver increases the possibilities of effective therapy, which is ensured by the properties of the laser and allows operations to be performed safely and with predictable results. This improves the patient's postoperative state, reduces the risk of complications and need for additional premedication, and ensures rapid healing [1-3]. A diode laser allows to make cuts of soft tissues depending on certain values of cutting modes. The parameters of the cutting modes are as follows: laser radiation power, pulse time and time between pulses, velocity of the medical instrument, and amount of air gap between the laser tip and biological tissue. When these parameters are set, it is possible to cut with different depths and widths depending on the operational requirements. Now, these operations are carried out manually, by a surgeon [4]. The surgeon, with the help of a medical instrument, performs manual movements along the required trajectories. To improve the quality of these movements, it is possible to use a robot [5-7]. To use a robot to perform cutting with a diode laser, it is necessary to prove the advantages of moving the medical instrument robotically. Therefore, it is advisable to compare the trajectories carried out by the surgeon with trajectories carried out with the help of a robot.

II. Obtaining Experimental Data

In order to compare the trajectories of a surgeon and a robot, it is necessary to obtain experimental data with regard to programmed and manual movements. Manual surgery is carried out by a surgeon, and the programmed movements are performed by the robot KUKA LWR4 +. To record the coordinates of points on the trajectories, a coordinate measuring machine is used—the laser tracker LTD800. The points are recorded by scanning the position of the LTD800 reflector fixed to a medical instrument at a frequency of 300 Hz along typical trajectories. These trajectories are set by analyzing the typical medical operations in the field of maxillofacial surgery [8,9]. Typical trajectories are divided into linear $l_i(x_i, y_i, z_i)$, semilunar $h_i(x_i, y_i, z_i)$, and scalloped

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$f_i(x_i, y_i, z_i)$, where i denotes the number of measured coordinates of points, $i = 1..N$, and N denotes the number of points on the trajectory. These trajectories as a set of position coordinates of the medical instrument and their visualization are shown in Fig. 1. When carrying out experiments to compare the trajectories of the movements of the robot and trajectories from the manual movements of the surgeon, instead of measuring biological tissue, the surface of the table $p_i(x_i, y_i, z_i)$ with minimal flatness is used to estimate the manual movements. Further, when determining the movements performed by the robot, the table surface is set using the program. This ensures that the evaluation results do not have the errors associated with the difficulties of setting trajectories and their comparison on surfaces of complex shapes (e.g., biological tissues).

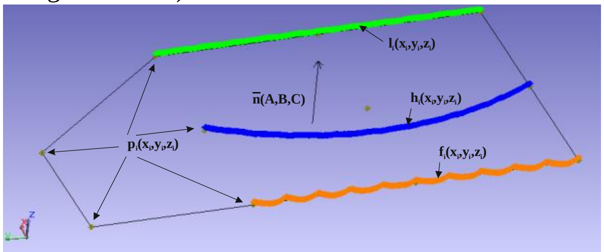

Figure 1. Set of medical instrument position coordinates on the linear $l_i(x_i, y_i, z_i)$, semilunar $h_i(x_i, y_i, z_i)$, and scalloped $f_i(x_i, y_i, z_i)$ trajectories.

To cut the required depth and width, it is necessary to constantly maintain the nominal (predetermined) cutting velocity or, in other words, the velocity of the tip of the medical instrument V_n (mm/s) at each point of the desired trajectory. During this cutting process, the surgeon, in view of the imperfections of his natural systems, makes uncontrollable velocity fluctuations with different amplitudes. A significant magnitude of this amplitude can cause additional micro trauma to the patient—burns or undercuts due to excess or lack of laser radiation at the time of cutting. In this situation, it will be necessary to make an additional passage along the same trajectory, which, in the case of cutting with manual movements, will also cause additional injuries due to the fact that a human cannot exactly repeat a passage along the same trajectory and with the same amplitude of oscillation velocity. To assess the velocity of movement on the trajectories of both the robot and surgeon, several comparison criteria based on the use of the ISO 9283 standard [10] were developed.

III. Standard Deviation from the Average Velocity as Criterion of Comparison

One of the main proposed criteria for comparing the velocity of the movement of robots and manual movements of a surgeon is the standard deviation of the cutting velocity σ_{Vr} (mm/s), i.e., the dispersion of the cutting velocity of one pass V_j (mm/s) on all the typical trajectories from the average cutting velocity V_m (mm/s). The criterion is presented in Fig. 2. For these studies, an estimate of the standard deviation of the cutting velocity is considered and can be determined using the following formula:

$$\sigma_{Vr} = \sqrt{\frac{\sum_{j=1}^{Q}\left(V_j - V_m\right)^2}{n-1}} \qquad (1)$$

The average cutting velocity, V_m, is defined as the arithmetic mean of the cutting velocities from each trajectory pass V_j ($j = 1...Q$, where Q is the number of passes). The standard deviations of the cutting velocity, σ_{Vr}, nominal cutting velocity, V_n, average cutting velocity, V_m, and average cutting velocity for one pass along the trajectory, V_j, are shown in Fig. 2.

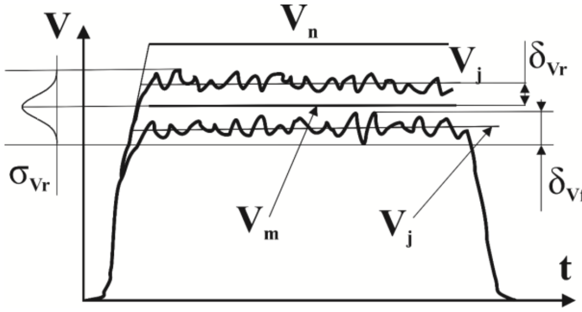

Figure 2. Criteria for comparing the cutting velocity of manual movements and movements performed by a robot: σ_{Vr}, δ_{Vr}, and δ_{Vfl}.

The cutting velocity of one pass V_j is defined as the arithmetic mean of the current cutting velocity V_{tk} on the trajectory. In turn, V_{tk} on each k segment of any typical trajectory is calculated in accordance with the following formula:

$$V_{tk} = \frac{r_{tk}}{T} \qquad (2)$$

Since the coordinates of the points were taken at a frequency of $\nu = 300$ Hz, the time through which each new coordinate is obtained is $0{,}003(3)$ seconds. The distance r_{tk} between each i ой point and $(i+1)$ point of any typical trajectory ($q_i(x_i, y_i, z_i)$ – l_i, h_i or f_i) is defined as follows:

$$r_{tk} = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \qquad (3)$$

where (x_i, y_i, z_i) are the coordinates of any typical trajectory for the robot and surgeon. Here, i denotes the number of measured point coordinates and k denotes the number that defines the segment r_{tk} for the current velocity. At the maximum number of points $i = M$, the maximum number of measurements of the current velocity is $k = M - 1$ on a single sample trajectory. The distance r_{tk} between the points of any typical trajectory $q_i(x_i, y_i, z_i)$ is shown in Fig. 3.

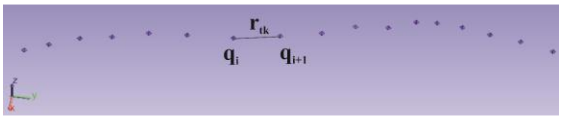

Figure 3. Distance r_{tk} between every i point and $(i+1)$ point of any typical trajectory $q_i(x_i, y_i, z_i)$.

To compare the cutting velocities of the surgeon and robot and to determine their standard deviations, statistical experiments were performed. The typical trajectories performed by a surgeon are divided into two categories: trajectories, the passages of which were carried out in the presence of a support point, e.g., the surgeon's hand touches the surface of the table during the passage, and the trajectories that do not involve touching ("in the air"). This is due to the need for the surgeon to hold the cutting tool differently during operations, depending on the openness of the operating field. Each sample trajectory was performed by the robot and the surgeon five times ($Q = 5$), and the cutting velocity V_j was obtained for each pass. In carrying out the comparison experiments, it was required from the test subjects to maintain a nominal cutting velocity equal to 10 mm/s at each distance r_{tk} for any typical trajectory. To compare the velocity of the tip of a medical tool within a single sample trajectory, both the robot and surgeon follow the same path. Scalloped trajectories are assigned to the robot along with smoothing. The results of the statistical experiments and the data of determining the values of the current cutting velocity on typical trajectories when moving by a robot are shown in Fig. 4. The results of the statistical experiments with manual movements with and without a support point are presented in Fig. 5 and 6. Each pass for each typical trajectory on the chart is highlighted in its own color.

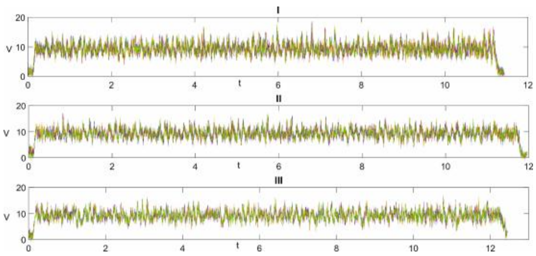

Figure 4. Graphs of changes in the values of the current cutting velocity V_{tk} (mm/s) from the measurement time t_{tk} (s) of the coordinates of the position of the medical tool when moving the robot along typical trajectories with five passes for each attempt (I: linear; II: semilunar; and III: scalloped).

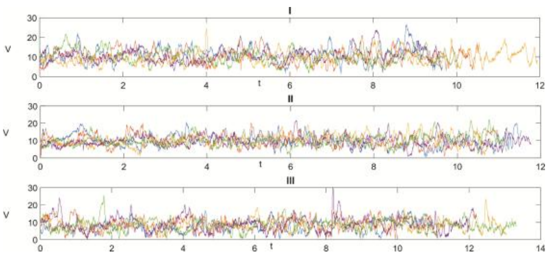

Figure 5. Graphs of changes in the value of the current cutting velocity V_{tk} (mm/s) from the measurement time t_{tk} (s) of the coordinates of the position of the medical tool during manual movement without a support point along typical trajectories with five passes in each attempt (I: linear; II: semilunar; and III: scalloped).

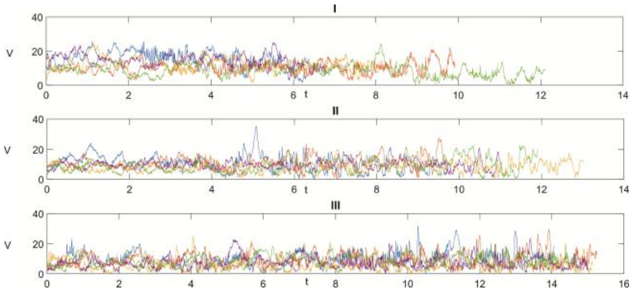

Figure 6. Graphs of changes in the value of the current cutting velocity V_{tk} (mm/s) from the measurement time t_{tk} (s) of the coordinates of the position of the medical tool during manual movement with a support point along typical trajectories with five passes in each attempt (I: linear; II: semilunar; and III: scalloped).

The increase and decrease of the current cutting velocity when moving by the robot along the typical trajectories in the sections at the beginning and end of the trajectory occur due to acceleration and braking. The calculation of the average cutting velocity V_m of the robot does not include the acceleration and deceleration portions. With manual movements, these parameters are not pronounced, so there is no need to filter them.

When analyzing the graphs obtained in Fig. 4, 5, and 6, we can conclude the identity of each trajectory in terms of velocity in general, i.e., regardless of the choice of the type of trajectory, the nature of the dependence of current velocity on the time of measurement does not change for the robot or surgeon. Therefore, it is possible to determine the value of the average velocity and standard deviation of the cutting velocity σ_{Vr} from the obtained data by combining all the typical trajectories into a single calculation. To calculate the average velocity in accordance with ISO 9283:1998, it is necessary to carry out at least 10 trajectories. When all the typical trajectories are combined, the number of trajectories j becomes 15. Thus, for calculating the criterion, 15 trajectories of all the manual movements with and without a support point and those moved by the robot are used, i.e., 3 datasets with a total of 51863, 50749, and 53705 units, respectively. The values of the standard deviation of the cutting velocity σ_{Vr} for the manual movements with and without a support point, as well as for movements performed by the robot, are listed in Table I.

TABLE I. VALUES OF CRITERIA FOR ESTIMATION OF CUTTING VELOCITY

	σ_{Vr} (mm/s)	δ_{Vr} (%)	δ_{Vfl} (mm/s)
Surgeon with support point	2.608	78	26.9
Surgeon without support point	0.979	29	26.3
Robot	0.038	1	14.8

The standard deviation criterion of the cutting velocity σ_{Vr} shows that the robot is 69 times more accurate in cutting velocity than the surgeon who conducts manual movements with a support point and 26 times more accurate in velocity relative to the surgeon who conducts manual movements without a support point.

IV. Additional Criteria

In addition to the standard deviation σ_{Vr}, an additional criterion must be used in order to quantify the stability of holding the required cutting velocity V_j for one pass of the robot relative to the surgeon, namely, δ_{Vr}, which denotes the repeatability of the cutting velocity (Fig. 2). Using the following formula, it is possible to determine the repeatability according to ISO 9283:1998:

$$\delta_{Vr} = \pm(\frac{3 \cdot \sigma_{Vr}}{V_n} \cdot 100\%) \tag{4}$$

The calculated values of the repeatability of cutting velocity δ_{Vr} for manual movements with and without a support point, as well as those for movements performed by the robot, are given in Table I. According to this additional criterion, it is revealed that the robot is 78 times more stable than the surgeon who conducts manual movements with a support point and is 29 times more stable with respect to the doctor/surgeon conducting manual movements without a support point. This indicates an excellent repeatability of the cutting velocity of the robot in relation to the repeatability of the cutting velocity of the surgeon.

With regard to the standard deviation and repeatability of the cutting velocity, the robot surpasses the surgeon by a large margin. However, with a more detailed comparative analysis of the graphs, it is also possible to identify one more additional criterion. For more successful detailing of this criterion, it is necessary to determine the nature of the distribution of the current cutting velocity V_{tk} for all the typical trajectories of the robot and that for the surgeon with and without a support point. Fig. 7 shows the histograms of the distribution of the value of the current cutting velocity V_{tk} for all the typical trajectories. The abscissa axis is the current cutting velocity V_{tk}, and the ordinate axis is the number of points in the selected interval P.

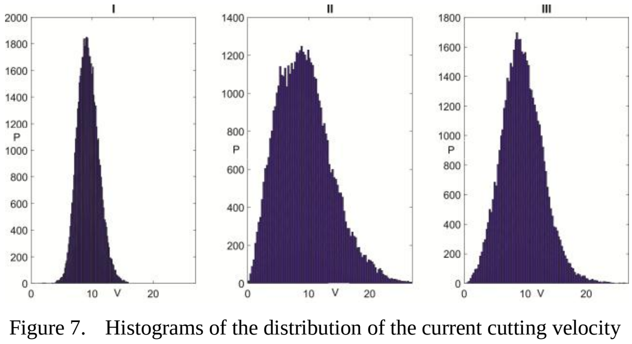

Figure 7. Histograms of the distribution of the current cutting velocity V_{tk} on all the typical trajectories when moving with the help of the robot (I), manual movement with a support point (II), and that without a support point (III) for all the typical trajectories.

According to the obtained histogram of the distribution of the current cutting velocity V_{tk}, the absence of normality in accordance with the Kolmogorov-Smirnov and Pearson tests was revealed. Therefore, for one more additional criterion for comparing the robot and manual movements, the value of the velocity fluctuation δ_{Vfl} is taken, and the difference between the maximum and minimum values of the current cutting velocity V_{tk} for each movement along all the typical trajectories is as follows:

$$\delta_{Vfl} = \max(V_{tk}) - \min(V_{tk}) \tag{5}$$

The velocity fluctuation values, δ_{Vfl}, for all the displacements are also presented in Table I. According to the obtained data, the robot has a smaller velocity fluctuation in the obtained values of the current cutting velocity V_{tk}, and therefore, by this criterion, exceeds the capabilities of the natural systems of the surgeon by a factor of 2. It should be noted that according to this criterion, since the robot is a complex mechanism, the comparative ratio can significantly increase due to the use of a higher-quality element base at the design stage of the medical robot.

V. Conclusion

The presented criterion quantitatively proves the expediency of using a robot for conducting medical operations with a diode laser in maxillofacial surgery. Further, it turns out that according to this criterion, namely, the standard deviation of the cutting velocity, the robot surpasses the natural systems of the surgeon who conducts manual movements with a support point by 69 times and by 26 times with respect to the surgeon who conducts manual movements without support points. According to the additional criterion, namely, the repeatability of the cutting velocity, it turns out that the robot is 78 times more stable than the surgeon performing manual movements with a support point and 29 times more stable with respect to the surgeon conducting manual movements without a support point. Furthermore, for one more additional criterion, namely, the velocity fluctuation in the velocity values, the robot is better than the surgeon by 2 times. Thus, it is proven that due to the use of a robot, it is possible to improve the quality of the conducted operations with the help of more accurate movements. Further researches will be directed on revealing reliable cutting modes and developing the mechanisms of cooperation between the surgeon and robot.

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