Force training for position/force control of massage robots

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Abstract. In the paper the force training mode for position/force control is considered. This problem is especially actual for medical robotic interacting with soft tissues during massage. The force training mode is necessary to control the deformation of human soft tissues, which have a number of features. It is proposed to extend the concept of the usual teaching geometric point with force information. This requires a sensor that measures the forces of interaction of the robot with the soft tissues. Such an approach for position/force control provides reproduction of path and forces imitating skilled physician. The psychophysiological efficiency is provided by biotechnical control circuit.

Key words: force training, position/force control, medical robot, soft tissues, massage.

Introduction

In 80 – 90's many investigations had been devoted to contact problems of a robotics. The scientific researches of robotic systems with force sensing are often left behind their practical use [7, 9]. The practice of contact problems is the following:

- in machining (cutting, grinding) it is necessary to support the assigned power (velocity, force) at a variable allowance of work piece;
- at burrs removal on the casts or list edge on the stamped details;
- at surface polishing with constant pressing force of the polishing tool on a detail;
- assembly problems which include the connection by a shaft insertion in the plug, and also carving connections;
- details extraction from nonoriented box with a necessary detail recognition and capture;
- force unloading of the loaded robot links;
- remote bilateral manipulators control;
- measurement and account of small deformations in aircraft designs speaking not only about robotics;
- manipulations on soft tissues and joints;

- in agriculture (plowing field).

One of the contact problems studied in lesser degree is soft tissue deformation by robots in restorative medicine. The restorative medicine includes a number of therapies including nonmedical, one of them is massage. Among a set of known means of massage the robotics possesses the greatest possibilities.

The history of massage robots occurrence in restorative medicine is the following. In 1997 the only work of robotics for restorative medicine was presented at the second forum IARP on medical robotics. That was the robot for massage [1]. In 2002 on a web-site of the Dutch firm a Tickle robot for massage appears as a tickling small insect [7]. In 2003 there was a Russian patent of the robot for train-massage [7]. In 2005 on a Silicon Valley web-site there was a message [8] about the Puma robot usage for massage purposes. The basis of this development was the idea stated in the Russian work [2, 3, 5].

However, the interaction of the robot with patient's soft tissues causes new approaches to position/force control, in particular in robot training. To train the robot the force training is proposed [6].

Despite a considerable quantity of papers in the field of contact problems, a number of problems both theoretical and practical remain unsolved. Therefore the problem of robot position/force control systems creation with easily realized regulators that allow quick and precise movements on any spatial trajectories with precise providing assigned forced influence is an actual one – whether it is possible to transfer known methods to control the medical robot performing manipulations on soft tissues.

To answer these questions we will address to the objects of manipulation. In known contact problems in industrial robotics they are rigid bodies. The interaction consists in pressing the robot to the rigid bodies (assembly, details joint definition at welding, polishing) or in pressing and cutting the rigid bodies (machining, cutting, grinding). The rigid bodies are considered as mechanical constrains which are known in advance and can be programmed.

1. Soft tissue features

The medicine defines a soft tissue (ST) as muscles, fascias, skin, fatty layer, ligaments, cartilages and tendons. Bones are rigid tissues. The mechanical characteristics of ST, in particular elastic coefficient and deformation value, have essential differences from the mechanical characteristics of details materials in assembly or machining.

It is necessary to note the distributed character of force loading during massage (Fig. 1) excepting acupressure. But further for contact interaction models we use the equivalent concentrated environment resistance force $\mathbf{F_e}$ which is balanced by drive force.

The certain force picture of the physician's hand or the robot tool interaction with a patient's body is given as a six-component vector:

$$\mathbf{F} = (F_x, F_y, F_z, M_x, M_y, M_z)^{\mathrm{T}}, \tag{1}$$

where F_x, F_y, F_z are projections of the force acting on the robot tool from patient's body,

M_x, M_y, M_z are the moments around axes x, y, z;

T is a transposing symbol.

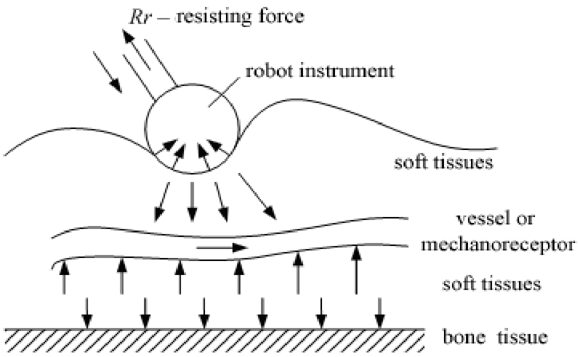


Fig. 1 Distributed character of force loading during massage.

In the most general model the ST can be presented as an anisotropic, multilayered, viscoelastic, plastic, inertial, and non-stationary environment [6].

In table 1 some typical massage techniques, movements, and force loadings are resulted. The masseur's hand parts or technical devices fixed on the end link of the robot can be used as a tool.

Table 1. Specific massage techniques, movements, and loadings.

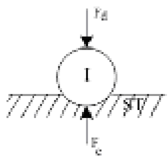
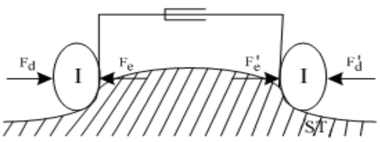
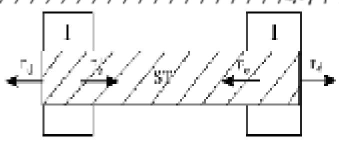
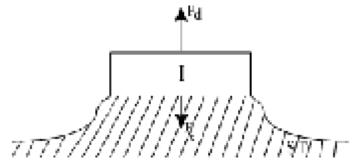
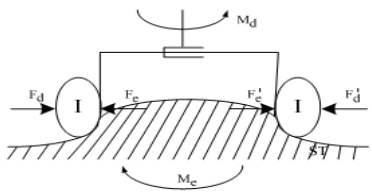
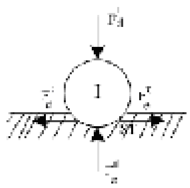
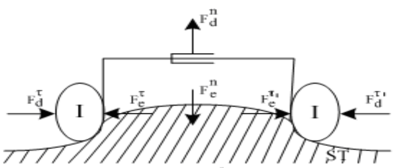
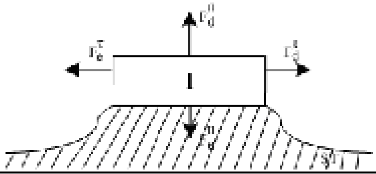
№	*Techniques*	*Resisting forces*
1	Palpation, shiatsu, force training	
2	Pincement	
3	Traction (stretch)	

Table 1. Continue

№	*Techniques*	*Resisting forces*
4	Vacuum massage (drawing)	
5	Pincement with spinning	
6	Pointillage with shear (without creeping)	
7	Petrissage, rubbing, squeezing (with creeping)	
8	Ordinary petrissage (with creeping)	
9	Vacuum massage (with creeping)	

In table 1 the following designations are introduced:

F_e, M_e are the force and the moment of ST resistance;

F_S, F_f, F_d are the force of elasticity, the ST friction force, the drive force.

The values of speed, forces and pressures on ST during typical movements are given in Table 2. These values determine the ranges only. The forces and the torques of drives should be balanced with the support reaction. The supports are necessary during both the manual and the robot massage. The bones of the patient's skeleton are less compliant than ST and they can be used as a support for pressing and stretching methods [7].

Table 2. The values of speed, strength, pressure on soft tissues developed in massage movements.

	Size of part, m	*Speed, m/s*	*Force, N*	*Area of contact spot, m^2*	*Pressure, Pa*
Stroking	0,01-1,0	0,01-0,3	<1	10^{-4} - 10^{-2}	$<10^{2}$
Squeezing	0,01-1,0	0,01-0,2	1-100	10^{-4}–$5 \cdot 10^{-3}$	10^{2}– 10^{5}
Pointillage	>0,02	0,01-0,3	1-30	$4 \cdot 10^{-6}$–10^{-4}	10^{4} – 10^{6}
Pressing kneading	(0,01-0,1)	0,01-0,3	1-100	10^{-4}–$5 \cdot 10^{-3}$	10^{2} – 10^{5}
Drawing petrissage	(0,01-0,1)	0,01-0,2	1-50	-	-
Traction	0,01-1,0	0,01-0,1	1-50	-	-
Pulse mobilization	-	0,1-1,0	50-200	$\sim 10^{-3}$	10^{5}

The ST elasticity measurement with a static method can be used not only for robot position/force control, but also to diagnose the patient's muscles state and patient's state in whole. On Fig. 2 the strain degree of forearm muscles (curves 1, 2) and hips (curves 3, 4) influence on $F_z = F(\Delta z)$, slope is shown.

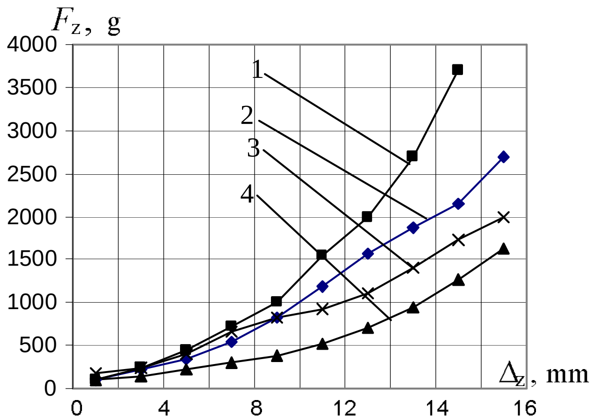


Fig. 2 Experimental curves $F_z = F(\Delta z)$, at various strain degree of muscles 1 – tense forearm, 2 – relax forearm, 3 – tense hip, 4 – relax hip.

The essential components of force interaction in massage are dry and viscous friction. The experimental dependence curve of the friction force on the speed is given on Fig. 3. The curve shows an increase of friction force due to viscous friction component.

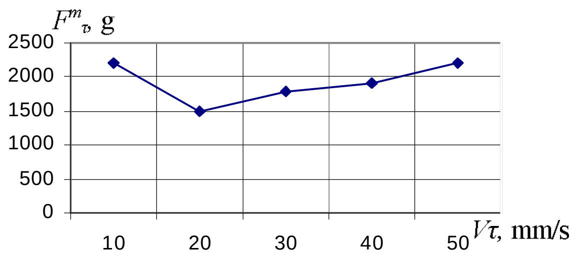


Fig. 3 Experimental dependence curve of the friction force on the speed.

We can interpret a massage as different types of force loading. For example, stroking is a wave of normal pressure on ST without shearing, rubbing is a shearing of skin and hypoderm, kneading is shearing and torsions of muscles, squeezing is a significant normal pressure on ST with shearing, squeezing by a roller is a wave of normal pressure on ST without shear.

2. Two control contours of massage robot

The main control purpose for medical robots is to lead patient's state variables to physiologically normal ones by means of robot mechanical influences (either directly on soft tissues or as manipulations on joints). Therefore it is necessary to consider two closed loop contours of force and biotechnical control, and also two basic control vectors: a vector of psycho-physiological state variables and a vector of measured forces of robot tool interaction with patient's ST (Fig. 4). The tool movement is also a control vector. In this system we consider a patient as a control object. In the contour of position/force control the patient's ST is a control object. In the contour of biotechnical control the converter of mechanical influence variables to variables of a psycho-physiological state is a control object [7]

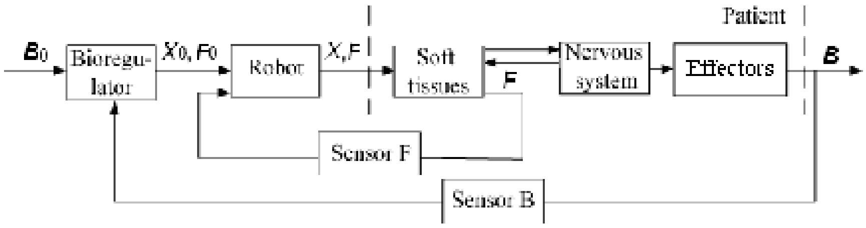


Fig. 4 Block diagram of bio-technical control system.

On Fig. 4 the following vectors are defined:

X, **F**, **B** are the vectors of real movement, force and patient's biomedical signals;

$\mathbf{X}_0$, $\mathbf{F}_0$ are the vectors of planned tool movement and assigned tool interaction force with the patient;

$\mathbf{B}_0 = (f, p, m, k, R)^{\mathrm{T}}$, is the vector of normal biomedical signals, for example, pulse rate, arterial pressure, signals of miography, muscular tone, electric skin resistance.

The impedance approach can be the basis of the robot position/force control [9]. An impedance control assumes providing a desirable balance between position and force errors developed on the robot end link. The block diagram of impedance control is shown on Fig. 5.

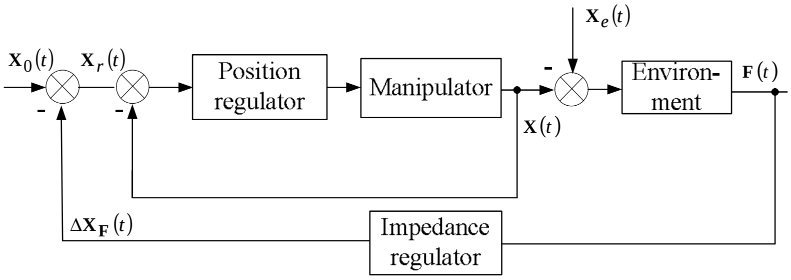


Fig. 5 Impedance control system.

On the block diagram the following designations are introduced: $\mathbf{X}_0$, $\mathbf{X}$ are the position trajectory desirable and real values, $\mathbf{X}_r$ is the value of the position trajectory corrected by impedance regulator, $\mathbf{X}_e$ is the relief of the environment contact surface, $\mathbf{F}$ is the real force value.

3. Force training in position/force control

Though main efficiency criteria of robots for restorative medicine are indicators of the patient's phychophysiologic state, the robot as a mean of massage should control mechanical contact interaction between a human arm (robot tool) and the patient's body. The computer vision systems working in various ranges, for example in X-rays, visible and ultrasonic light are possible for control. These systems allow to see ST structure, their location concerning bone tissues. This is vast but expensive information.

There is an experience of blind masseurs with highly developed tactile sensation that allows to memorize, control and mark progress in procedure performance. Therefore we can talk about designing of robots using force information about ST relief and viscoelastic properties [7].

For massage the controlled variables and control aims can be the follows:

- during the surface stroke and the minimum contact forces the constant velocity should be provided on a trajectory: V =const;

- on body parts with homogeneous properties it is desirable to support constant force: F = const;

- at deep massage with the high forces the masseur is compelled to reduce velocity when the hand meets the high resistance, therefore achievement of a constant power is relevant $N = F \times V = \text{const}$;

- to perform the long work the masseur has to save his energy, so the minimal energy expenses can be his aim;

- it should be taken into account that massage is performed using the tools or hands with various contact surfaces, therefore it is necessary to support assigned forces per unit of contact surface square that is pressure $p = F/S$.

Generally the vector $\mathbf{X}(t)$ represents spatial position and orientation co-ordinates. For example,

$$\mathbf{X}(t) = (\mathbf{n}, \mathbf{s}, \mathbf{a}, \mathbf{p})^{\mathrm{T}}, \tag{2}$$

where **n**, **s**, **a** are the orientation subvectors, **p** is the subvector of tool position, or

$$\mathbf{X}(t) = (x, y, z, o, a, t)^{\mathbf{T}}, \tag{3}$$

where x, y, z are the position co-ordinates, o, a, t are Euler's angles of tool orientation.

Generally force/torque vector $\mathbf{F}(t)$ is represented as a six-dimensional vector

$$\mathbf{F}(t) = (F_X, F_Y, F_Z, M_X, M_Y, M_Z)^{\mathrm{T}}, \tag{4}$$

where F_X, F_Y, F_Z are the forces along axes of basic or tool co-ordinates system, and M_X, M_Y, M_Z are the moments around these axes.

Then the problem of position/force control is posed as providing the position trajectory $\mathbf{X}(t) \to \mathbf{X}_0(t)$ and the force trajectory at contact interaction of the robot tool with the patient's body $\mathbf{F}(t) \to \mathbf{F}_0(t)$. The problem of force control provides $\mathbf{F}(t) \to \mathbf{F}_0(t)$ at any uncontrollable moving $\mathbf{X}(t)$.

It is necessary to note the following position/force control law of the robot interacting with the environment: in an uncertain or variable environment it is impossible to provide the assigned robot interaction force with this environment simultaneously and precisely on any assigned trajectory, i.e. to provide $\mathbf{X}(t) = \mathbf{X}_0(t)$ and $\mathbf{F}(t) = \mathbf{F}_0(t)$ simultaneously. It is possible precisely provide only one variable, either $\mathbf{X}(t)$ or $\mathbf{F}(t)$, conceding other variable.

There are several methods to define a spatial trajectory: by means of defined reference points; by means of points or continuous curves transferred, for example, from computer vision system; by means of trained points or curves from a manual control.

To assign the interaction forces on a spatial trajectory the following methods are known: assign the forces with a keyboard and using a force setting device. A diagnostic strain glove and methods of preliminary ST force scanning can be actual methods of force settings for massage problems.

The offered adaptation arranges system not only in the phase of the basic procedure execution, but in preliminary environment probing. The training procedure is interactive and it allows to take into account individual features of a patient.

Traditional for industrial robotics training assumes manual robot tool approach to a necessary point near contact or in contact. Then the position sensors measure joint coordinates and memorize them.

A trained point can have the same number of coordinates as the number of manipulator's drives. This is called training in the joint generalized coordinates **q**.

$$\# A(q_1, q_2, ..., q_n). \tag{5}$$

As a rule the six-joint robots have an inverse kinematic task solver and can transform precision (generalized) point coordinates to the Cartesian ones:

$$\# A(q_1, q_2, ..., q_n) \rightarrow A(x, y, z, o, a, T), \tag{6}$$

where *x, y, z, o, a, T* are robot end link target position and orientation coordinates.

$\mathbf{X} = F(\mathbf{q})$ and $\mathbf{q} = F^{-1}(\mathbf{X})$ represent the direct and inverse kinematic tasks.

Further named force trained point in addition to geometrical coordinates includes components of interaction force vector between the robot tool and a patient's body. Generally vector **F** has six components.

$$\mathbf{F} = (F_X, F_Y, F_Z, M_X, M_Y, M_Z)^{\mathrm{T}}, \quad . \tag{7}$$

These components can be measured by a six-component force sensor fixed on a robot end link between the flange and the tool. Therefore vector **F** components are measured in moving tool coordinates system.

The measurements are made at stop in a trained point. It is possible to calculate these components using force sensors located in joints.

$$\mathbf{F} = \left(J^T\right)^{-1} \mathbf{F}_t , \tag{8}$$

where $\mathbf{F}_t = (F_{t1}, F_{t2}, ..., F_{tn})^{\mathrm{T}}$ is the vector of forces and moments in joints.

Then the force trained point A is represented by twelve-dimensional vector:

$$A(x, y, z, o, a, T, F_X, F_Y, F_Z, M_X, M_Y, M_Z)^T . \tag{9}$$

Training can be performed either by means of points or continuously. Usual continuous positional training assumes recording the spatial curve in time. In case of continuous force training in addition to continuous geometrical coordinates the point will contain measured force components, for example

$$A(x, y, z, o, a, T, F_Z). \tag{10}$$

At points force training before massage procedures a tool "penetrates" into a ST until the force sensor indication is equal to the assigned force. The robot drives stop and position and orientation coordinates together with the reached forces are memorized.

At manual training a point is memorized with the tool axis orientation directed to a normal to a deformed ST surface. At automatic training of ST area by scanning a plane frame is assigned with denoting of only three point coordinates for example $A(x, y, z)$ with identical tool axis orientation without normals definition. Later with approximately calculated normals from the first automatic scanning we can repeat scanning specifying normals orientation.

Generally the force trained point can contain not only pressing forces but also forces of ST stretching, torsion, bending and tangential component.

4. Position/force control with force training realization

Force training allows to perform the second phase of the position/force control as a positional tracking. This enables to use usual robots without force correction tracking. If a robot is able to perform the force correction then the quality of control generally increases. On Fig. 6 the curve $L_0(\mathbf{X}_0, \mathbf{F}_0)$ represents the trajectory of the robot tool when $\mathbf{X}(t) \to \mathbf{X}_0(t)$ and $\mathbf{F}(t) \to \mathbf{F}_0(t)$. The curve $L(\mathbf{X},\mathbf{F})$ represents the trajectory of the robot tool after usual position training which depends primarily on surface relief. The curve $L_0(X, F)$ represents the trajectory of the robot tool after force training when the required accuracy is achieved.

$$\left\| L_0(\mathbf{X},\mathbf{F}) - L_0(\mathbf{X}_0,\mathbf{F}_0) \right\| < R \qquad (11)$$

where R is the radius of the sphere, which determines the positional error.

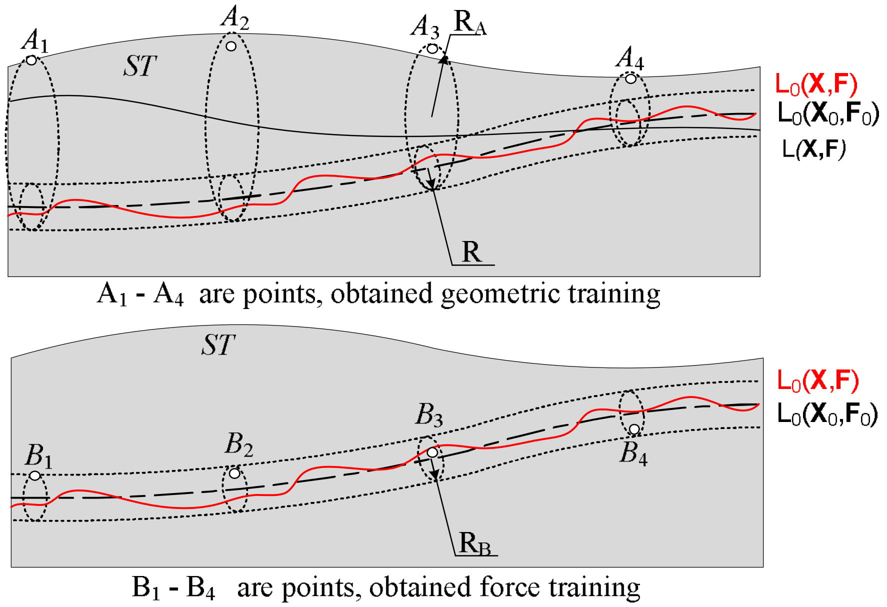


Fig. 6 The position/force control accuracy in position or force training.

At Moscow State Industrial University the robot performing massage and extremities movements techniques is developed [4-6]. A basis of this robot is the industrial PUMA robot that has anthropomorphic manipulator (Fig. 7). The robot provides the contact force up to 60 N. On the end link a force module containing a strain gauge is mounted. Necessary efforts are made and supervised by position/force control system expanding possibilities of the standard robot.

Fig. 7 Robot with position/force control for massage developed in Moscow State Industrial University.

The six-drive robot can perform a set of known manipulations directly on soft tissues, i.e. various massage, and also manipulations on joints in the form of passive and active extremities movements, a post-isometric relaxation (loading and unloading combinations for extremities muscles).

Conclusions

The soft tissues as an environment interacting with the robot have properties different from constructional materials. The force training mode as a phase of position/force control is preferred for robots deforming ST in massage. This mode was realized with the use of the modernized robot PUMA. Clinical trials of the robot performing various massage techniques on different patients have confirmed the effectiveness of the proposed force training mode.

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