Mechanism Design and Analysis of A Foot Massage Robot

Shiyu Xiao\textsuperscript{1,2,a}, Hongguang Wang\textsuperscript{2,b}, Donghua Ma\textsuperscript{3,c}, Yong Jiang\textsuperscript{2,d}, Yong Chang\textsuperscript{2,e} and Peitian Cong\textsuperscript{1,f}

\textsuperscript{1}School of Mechanical Engineering, Shen Yang Ligong University, Shenyang 110159, China
\textsuperscript{2}State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China
\textsuperscript{3}Ningxia Polytechnic, Yinchuan 750021, China
\textsuperscript{a}xiaoshiyu@sia.cn, \textsuperscript{b}hgwang@sia.cn, \textsuperscript{c}xjymadonghua@126.com, \textsuperscript{d}jiangyong@sia.cn, \textsuperscript{e}changyong@sia.cn, \textsuperscript{f}13904049316@163.com

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Abstract. Combining the traditional Chinese-medicine theory and the modern robot technology, a new type of massage robot that can accurately locate the acupuncture points and implement the acupuncture point-matching treatment has been proposed. A serial-parallel mechanism is adopted as the main mechanism of the massage robot that has the merits of not only compact structure and dexterous movement, but also realization of the motion decoupling from the force control of the massage mechanism. Based on the introduction of the foot massage robot system and its function, both the analysis of the mechanism and the optimal design have been completed to meet the design requirements. The kinematics model has been established. The simulation and experimental research have been carried out and verified the rationality of the design and the feasibility of the scheme.

Introduction

Clinical trials show the treatment method that combines massage techniques with acupuncture point-matching has high cure rate for hypertension. However, foot massage techniques are mostly transmitted in handing-down teaching mode. Due to different massage techniques and nonstandard operational procedures, the acupuncture point-matching scheme, the point position, the force and its angle, and the frequency are different from each other, which have a great influence on therapy. These problems will lead to the scientific and normative Chinese-medicine foot massage \cite{1} not to get promotion.

At present the researches \cite{2,3,4} of medical massage robot are studies in Europe, the United States and Japan, for example of the medical rehabilitation robot \cite{5} fabricated by Japan waseda university. This robot is mainly composed of two series arms, plunger device and end actuator. Although it can offer massage treatment on facial acupuncture points by using hybrid position/force control method and be used for curing oral health problems such as jaw dislocation, dry mouth, difficulty swallowing, it has huge volume of mechanical system and complicated control system just as the industrial mechanical arm. In recent years, domestic research institutes also begin to pay close attention to the research of this aspect, for example Lvzhong Ma, a professor of Jiangsu university, who develops a new type of traditional Chinese-medicine massage robot\cite{6} basing on parallel mechanism. This parallel robot with five degrees of freedom can realize traditional Chinese medical massage in rolling and some other methods. However, those robots that can realize the accurate positioning and the acupuncture point-matching massage are rarely reported. Foot massage products in the markets, due to adopting mechanical vibration, rolling pressure, friction, balloon extrusion, infrared ray and heat treatment methods to achieve massage, do not have the acupuncture point positioning function and can't simulate the techniques of traditional Chinese-medicine massager.

Combining traditional Chinese-medicine theory with modern robot technology, a kind of foot massage robot that can realize accurate positioning and auxiliary treatment with acupuncture point-matching is proposed. The main mechanism of this robot is a serial-parallel mechanism that makes the robot has the merits of not only compact structure and dexterous movement, but also realization of decoupling of the movement of the mechanism from the force control of massage.
Robot system

Foot massage robot system consists of robot body and controller. The robot body is mainly composed of shell, supporting frame, foot massaging mechanism and positioning and clamping mechanism, as shown in Fig.1. When the feet have been put into the robot, they will be fixed on foot massage platform by positioning and clamping mechanism and the sensors measure feet code. Then the controller of robot body sets programs and trajectory of massage mechanism basing on the foot code information, and then the massage mechanism can realize the accurate positioning and acupuncture point-matching treatment on these grounds. According to the patient's actual conditions, different treatment programs can be chosen. These programs include massage force, acupuncture point-matching process, treatment time and massage frequency, etc.

Fig.1 The body of foot massage robot

For foot massage robot body, the design of massage mechanism is the key to simulate the techniques of traditional Chinese-medicine massager and realize accurate positioning and acupuncture point-matching treatment.

Design requirements

Working space: according to the size of ordinary people's foot, foot massage robot is designed for the foot code from 35 to 43. On the basis of GB/T3293.1-1998 the standard size of 43 foot code is 0.265 m × 0.097 m and the maximum depth of foot concave is generally no more than 0.030m. Since the front parts of the feet do not need massaging, the 0.250 × 0.105 × 0.030 m³ area is chosen for working space of massage contact.

Force of massage: in the respect of foot clinical medicine, the size and the direction of massage force are important factors that influence the massage effect. The massage force should make the massaged person feel a slight ache and not feel dismayed, dizziness, nausea, etc. If it is too light, it does not work; if overweight, it may cause some damages, such as ligament, muscle and fascia tissue injury. If the massage force is appropriate and approximate constant, the treatment effect will be better. According to expert's practice research, massage force can be divided into four grades aiming at the different massage demands, and they are 11.76 N, 24.50 N, 58.80 N and 63.70 N, and the protecting force of the mechanism is 70 N.

Massage track: according to the massage requirements of the acupuncture point reflection on foot bottom, the massage movement may along the width or length direction of the foot, or the direction with a certain angle. So massage contact must realize a "mi" glyph movement at single acupuncture point reflection, and the vertical direction is along the length direction of the foot.

Comprehensive mechanism analysis

According to the kinematics and dynamics characteristics about traditional Chinese-medicine massage [7], pushing method is mostly appropriate for foot massage robot to do massage treatment. This method includes applying force on one part of patients along direction of foot plane by fingers, hands or elbows, moving on along a certain in-plane direction, and proceeding to the next round.
Factually, the action of the Chinese-medicine massager who uses pushing method to massage under foot plane is a kind of complicated hybrid position/force control-mode. In order to effectively simulate massagers’ techniques, the massage mechanism adopts a kind of series-parallel structure to ensure proper position of massage contact through parallel positioning mechanism and proper massage force through spiral feeding mechanism. The foot massaging mechanism is shown in Fig.2.

This mechanism consists of a parallel positioning and spiral feeding mechanism. As shown in Fig.2(a), screw 5 and 6 are respectively driven by motor 2 and 3 and makes the sliding block 7 and 8 move along the rail, then the position of the intersection—the foundation of the spiral feeding mechanism—is determined. As shown in Fig.2(b), screw 15 is driven by motor 18, and it drives the massage contact 17 and achieves feed movement in working space along the z axis.

Basing on the design requirements, the massage mechanism needs parameters optimization so as to get smaller volume, lighter weight and better mechanical properties. The optimal items include the length of the connecting rod, screw spacing and screw effective length. For spiral feeding mechanism, the effective screw length should be no less than the height of the z axis direction in working space, so the effective screw length is 0.030m; for parallel positioning mechanism, in order to guarantee good transmission performance, the maximum pressure angle should be less than 40°, as shown in Fig.3.

In Fig.3, the pressure angles are α and β, the length of connecting rod is l, the rectangular ABCD is working space and its width and length are l₁ and l₂, dotted line gh and mn are sliding block guide-rails and the guide-rails are symmetric about the working space and 2 k wider than the working space, the effective screw length is y, the mechanism length is z. For different parameter k, there is Eq.1:

\[
\begin{align*}
  y &= l_2 + \sqrt{l^2 - k^2} - \sqrt{l^2 - (l_1 + k)^2} \\
  z &= l_2 + \sqrt{l^2 - k^2} \\
  (\sin \alpha)_{max} &= (\sin \beta)_{max} = \frac{l + k}{l}
\end{align*}
\]

Since the massage contact is a round head whose diameter is about 0.010m and must be in the space between the two screws, we can suppose that width parameter k changes by tolerance for 5 arithmetic progression in [5, 30] and x=l. Curves (x, y) and (x, z) are drawn, as shown in Fig.4.

According to the design requirements and the maximum pressure angle condition, we select parameter k=5. Consequently the length of the connecting rod is 0.171m, the center spacing of the two screws is 0.115m, the effective screw length is 0.290m, the mechanism length is 0.421 m.
Kinematics modeling

According to the mechanism parameters, the kinematics model of parallel positioning mechanism is established. As shown in Fig.5, the X axis is parallel with the guide-rails, the Y axis is perpendicular to the guide-rails and the mechanism plane overlaps the plane $xoy$; E and F represent for the position of the sliding blocks, G for the position of massage contact, H for the position of massage contact end and O’ for the intersection point about the center line of working space and the heel. The origin coordinates can be determined by the mechanism length.

Supposing the displacement of sliding block are $s$ and $t$, the displacement of massage contact is $r$, the coordinates of massage contact end are $(x, y, z)$, the length of massage contact is $r_0$. If we know the coordinates of massage contact end, according to the geometrical relationship, the input quantity $s$, $t$ and $r$ can be obtained from Eq.2:

\[
\begin{align*}
  t &= x - l \cos(\arcsin((l_y - y + 2k)/l)) \\
  s &= x - l \cos(\arcsin(y/l)) \\
  r &= z - r_0
\end{align*}
\]

If we know the input quantity $s$, $t$ and $r$, the coordinates of massage contact end can be obtained from Eq. 3 and Eq. 4:

\[
\begin{align*}
  x &= \frac{-B + \sqrt{B^2 - 4AC}}{2A} \\
  y &= \frac{(s - t)x + (l_i + 2k)}{l_i + 2k} + \frac{(r^2 - s^2 + (l_i + 2k)^2)}{(l_i + 2k)} / 2 \\
  z &= r + r_0
\end{align*}
\]

Eq. 4 is a supplement to Eq. 3.

\[
\begin{align*}
  A &= (s - t)^2 / (l_i + 2k)^2 + 1 \\
  B &= -(s + t)(s - t)(l_i + 2k)^2 / (l_i + 2k) \\
  C &= (t^2 - s^2 + (l_i + 2k)^2)^2 / 4(l_i + 2k)^2 + s^2 - l^2
\end{align*}
\]

Kinematics simulation

According to the actual situation of the experimenter, the reflection areas of his nine important acupuncture points are approximately drawn in the plane $xoy$. As shown in Fig.6, there is a certain angle between reflection area E and X axis and between reflection area J and X axis($\gamma = 60^\circ$, $\delta = 25^\circ$), other reflection areas are parallel with X axis.
In order to ensure smooth massage movement and no shocking velocity and acceleration, straight path from point to point is adopted to plan the motion of massage contact in plane $xoy$, Eq. 5 represents the motion law of massage contact:

$$
\begin{align*}
\begin{cases}
\ddot{s}(t) &= \ddot{s}_x + (\ddot{s}_y - \ddot{s}_x)g(t), 0 \leq g(t) \leq 1, \\
\tau &= t / T, t = [0, T] \\
\ddot{s}(t) &= (\ddot{s}_y - \ddot{s}_x)g'(t) / T \\
\dddot{s}(t) &= (\ddot{s}_y - \ddot{s}_x)g''(t) / T^2 \\
g(t) &= \tau - \sin(2\pi\tau) / 2\pi \\
g'(t) &= 1 - \cos(2\pi\tau) \\
g''(t) &= 2\pi \sin(2\pi\tau)
\end{cases}
\end{align*}
$$

Among them, the initial position, the final position and the orientation of the straight path can be obtained from the shape and orientation of the reflection of acupuncture points and the massage trajectory requirements. Supposing the angle between the move direction of massage contact and the X axis is $\theta$, motion simulation analysis is done according to some typical points in the nine important acupuncture points.

Supposing the center coordinates of one acupuncture point are $(x_0, y_0)$, the length of the reflection area along the direction of contact movement is $2p$, the displacement along X direction is $x$, its initial value is $(x_0 + p\cos\theta)$, its terminal value is $(x_0 + p\cos\theta)$; the displacement along Y direction is $y$, its initial value is $(y_0 + p\sin\theta)$, its terminal value is $(y_0 + p\sin\theta)$; the whole displacement is $s$, the speed is $v$, the acceleration is $a$. If massage contact moves from reflection area G to reflection area E and massages at reflection area E, the motion laws of slide blocks can be obtained according to the geometrical relationship in Fig.5 and the motion law of the massage contact in Eq. 5. The motion laws of slide blocks are shown in Fig.6.

Fig.6 shows that the velocity and acceleration of massage contact and slide block are smooth during massaging. The kinetics simulation basing on the typical reflection of the important acupuncture points verifies that the massage mechanism works very well, and the trajectory curve of massage contact is shown in Fig.7.
Experimental verification

According to the above motion planning, movement test of massage contact is done based on several acupuncture points of one experimenter, as shown in Fig.8.

Test results show that the serial-parallel design is able to realize the accurate positioning about foot acupuncture points and acupuncture point-matching massage, the massage mechanism can effectively simulate the techniques of traditional Chinese-medicine massager and offer standard massage treatment for patients through hybrid position/force controlling.

Conclusions

Aiming at the problems about foot massage methods during practical application and combining the traditional Chinese-medicine theory with modern robot technology, this paper presents a new type of foot massage robot, which can realize accurate positioning about foot acupuncture points and auxiliary treatment with acupuncture point-matching massage. The massage mechanism of this robot adopts the series-parallel design, thus the movement of the mechanism is decoupled from the force control of massage and the robot structure is compact and massage action is dexterous.

According to the design requirements, comprehensive analysis and optimal design about massage mechanism are implemented; the kinematics model is established; simulation and experimental research are carried out and the rationality and feasibility of mechanism design are verified.

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