Spinal Physiological Motion Simulator and Compensation Method for a Robotic Spinal Surgical System

Bing Li, Haiyang Jin, Min Fang, Ying Hu* and Peng Zhang

Abstract—**During spinal surgery, spinal physiological motion (SPM) due to respiration can interfere with the operation. The patient is anesthetized and breathes passively with the aid of a ventilator, causing periodic SPM. In this paper, a respiratory model based on the ventilator flow waves is proposed; and a spinal physiological motion simulator (SPMS), which is based on a 3-RPS parallel mechanism, is developed for simulating the SPM due to the respiratory model. For compensating the SPM, a compensation algorithm based on weighted frequency linear combiner (WFLC), which can adapt to variation in the frequency and amplitude of a quasi-periodic signal, is proposed for a robotic surgical system in this paper. And finally, two experiments were carried out, one to analyze the SPMS error and the other to validate SPM compensation using the compensation algorithm.**

Keyword—**surgical robot, physiological motion, 3-PRS, WFLC, motion compensation**

I. Introduction

Advances in science and technology have led to the use of a variety of surgical robots in the field of medical application. Interference due to physiological motions from respiration and cardiac rhythms pose a problem for the development of specialized surgical robots, in that the motion will reduce the operation accuracy and stability. To overcome these issues, many scholars focus on the researches of the characteristics and compensation method of these physiological motions. And some physiological motion simulators are also developed for these researches and experiments. Such as the 2-Degree of Freedom (DoF) device designed by Gangloff et al., to research respiratory motion compensation [1], which can simulate some simple physiological motions of organs. For the experiment of spinal fusion, a respiratory motion simulator emulating a human respiratory movement was developed by Chuang et al. The simulator is based on a 3-DoF parallel robot [2], however, the research for the characteristics of the respiratory movement wasn't reported. Wong et al. developed a testing device for respiratory motion compensation [3], which is a computer controlled 3-axis motion simulator with high flexibility. Due to the translational degrees of freedom, its simulation contained translation but no rotation.

Also, there are many methods used for physiological motion compensation, which can be classified as the active compensation and the passive compensation. The active compensation is more commonly used in robotic surgery systems and is implemented using a compensation algorithm. Gangloff et al. [1] propose a repetitive model predictive control (RMPC) algorithm to drive a surgical robot toward the reference trajectory in teleoperated laparoscopic surgery. Cavusoglu et al. [4] actively track and cancel the relative motion between the surgical instruments and the heart using an active relative motion cancelling (ARMC) algorithm, allowing surgeries to be performed on a beating heart with technical perfection equal to traditional on-pump procedures.

Another commonly used compensation algorithm is the Fourier linear combiner (FLC) for human physiological motions, which is mostly periodic. The FLC is suitable for the estimation of periodic signals of known frequency. The weight-frequency Fourier linear combiner (WFLC) algorithm, an extension of the FLC, can adapt to variation in the frequency and amplitude of a quasi-periodic signal. In [5], the WFLC is used by Riviere et al. to model and predict respiratory movement in a robotic system used for percutaneous kidney surgery. Ang et al. [6] use the WFLC algorithm as an adaptive frequency estimator to provide the instantaneous dominant frequency of the signal of interest to the system, allowing adjustment of the filter coefficients to yield the required performance. Thakral et al. [7] model rodent chest and heart wall motion using the WFLC algorithm.

During spinal surgery, the patient is anesthetized and is unable to breathe spontaneously. The patient breathes with the aid of a ventilator, which is a device that controls the airflow into the patient's lungs. As the control cycle of a ventilator is periodic, it also makes the patient's respiration periodic. In this paper, for experiments and researches of robotic spinal surgical system, a spinal physiological motion simulator (SPMS) is designed to simulate the spinal physiological motion (SPM) caused by the respiration of the patient. By building the relationship between the flow wave of the ventilator and the motion of the patient's spine, five typical movement models are obtained for driving the SPMS. A compensation algorithm based on WFLC is proposed to compensate the SPM in operation, and the algorithm is tested by the milling experiments using a 3-axis Cartesian robot and the SPMS.

The remainder of this paper is organized as follows. The

This work is supported by National Natural Science Foundation of China (No. 61175124), Guangdong Innovative Research Team Program (No. 201001D0104648280) and Shenzhen Fundamental Research Fund (No. JCYJ20140417172417129) .

Bing Li and Min Fang are with the Harbin Institute of Technology Shenzhen Graduate School, Shenzhen, China. (e-mail: libing.sgs@hit.edu.cn and 1006412428@qq.com).

Haiyang Jin, Ying Hu*(corresponding author) and Peng Zhang are with Guangdong Provincial Key Laboratory of Robotics and Intelligent System, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences. (e-mail: hy.jin@siat.ac.cn, ying.hu@siat.ac.cn and zhangpeng@siat.ac.cn).

second section introduces the respiratory motion compensation algorithm based on WFLC in detail. The third section shows how we designed the SPMS and built the model of spinal respiratory motion. The fourth section details the experiments for SPMS and respiratory motion compensation. The last section gives the conclusion of the paper.

II. Motion Compensation Based on WFLC

A. Spinal Physiological Motion Prediction

Many different extensions of the FLC have been successfully applied in physiological motion compensation. The WFLC is one of these. As the FLC only deals with periodic signals of known frequency, the purpose of the WFLC is to estimate periodic signals of unknown frequency and amplitude. Another advantage of the WFLC over the FLC is that it can adapt to time-varying reference signal frequencies using a modification of the least mean square (LMS) algorithm [8].

The WFLC algorithm forms a dynamic truncated fourier series model of the prediction of SPM y_{k+1}, shown in (1).

$$y_{k+1} = \sum_{r=1}^{M} [a_r \sin(r\omega_0 k) + b_r \cos(r\omega_0 k)] \tag{1}$$

where M is the number of harmonics in the model, k is the time index, ω_0 is the fixed reference frequency of FLC, a_r and b_r are the amplitudes of the rth sine and cosine harmonics. The WFLC algorithm extends the FLC algorithm to adapt to the time-varying reference signal frequency by a modification of the LMS algorithm. It can be expressed as follows.

$$x_{rk} = \begin{cases} \sin(\mathrm{r}\sum_{t=0}^{k}\omega_{0t}) & 1 \le r \le M \\ \cos((\mathrm{r}-\mathrm{M})\sum_{t=0}^{k}\omega_{0t}) & \mathrm{M}+1 \le r \le 2M \end{cases} \tag{2}$$

$$\begin{aligned} \varepsilon_k &= s_k - W_k^{\mathrm{T}} X_k \\ \omega_{0k+1} &= \omega_{0k} + 2\mu_0 \varepsilon_k \sum_{r=1}^{M} r(a_{rk} x_{(M+r)k} - b_{(M+r)k}\, \mathrm{x}_{rk}) \\ W_{k+1} &= W_k + 2\mu X_k \varepsilon_k \end{aligned} \tag{3}$$

where W_k=[$a_{1k}\ a_{2k} \ldots a_{Mk}\ b_{1k}\ b_{2k} \ldots b_{Mk}$] and X_k=[$x_{1k}\ x_{2k} \ldots x_{3k}$] are the adaptive weight vector and reference input vector, respectively. The adaptive weight vector W_k is used to estimate the amplitude and phase of the input signal, while the reference input vector X_k makes a contribution to the tracking of the signal amplitude involving the raw signal s_k. ω_{0k+1} estimates the unknown fundamental frequency, and μ_0 and μ are the gain parameters for the adaptation of frequency and amplitude, respectively.

B. Compensation Method for a Robotic Surgical System

With motion prediction by WFLC, the trend of a quasi-periodic respiratory motion, such as SPM, can be gained and compensated in the control loop of the surgical robot. Fig. 1 shows the whole process of the SPM compensation method proposed in this paper. The position and motion of the operation object is recorded by a tracking device. After a short time observation (10 seconds in this paper), the prediction model of the SPM of the patient is calculated. The predicted SPM is used to compensate the original input operation commands, and then, the compensated motion commands are sent to the control system of the robot and drive the robot move with motion compensation.

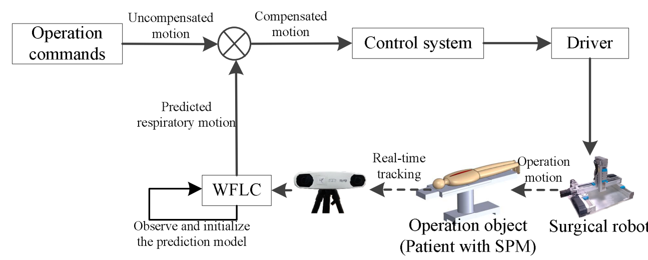
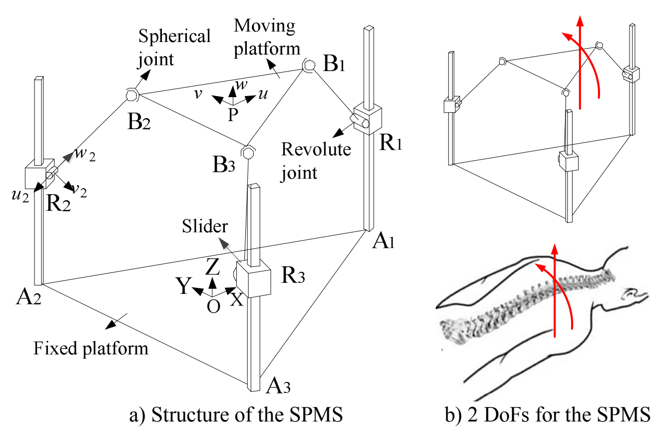


Fig. 1. Operation with motion compensation for a surgical robot

III. Development of the SPMS

A. Structure Design of the SPMS

The simulation of the SPMS has two purposes: one is to simulate the fluctuation, with even amplitude, of thoracic or lumbar motion, and the other is to simulate the fluctuation with uneven amplitudes between the thoracic and the lumbar spinal motion. The simulation, therefore, needs to accomplish 2-degrees of freedom (DOFs) movement, including a translational movement along the vertical direction and a rotational movement around a horizontal axis. Taking into consideration the control accuracy, load capacity and function transformation of the future simulator, we select the 3-PRS PM for the main structure. In comparison to a serial mechanism, PM has higher control accuracy, greater stiffness and a stronger load capacity. Additionally, the 3-PRS PM has three DOFs, and so can accomplish more complex movement.



a) Structure of the SPMS b) 2 DoFs for the SPMS

Fig. 2. Schematic of the SPMS

Fig. 2a shows the structure of the SPMS, and Fig. 2b shows the required DoFs in simulating SPM. Its design requirements are described as follows. The vertical stroke of the moving platform is 20 mm and the overturning angle range around the horizontal axis is 10°. Based on the design requirements, we determined the dimensions of the structure and analyzed its flexible workspace.

The 3-PRS PM has three DOFs, a translational DOF along the Z axis and two rotational DOFs around the X axis and the Y axis, which theoretically determine its working area as a straight line. However, the two rotational DOFs cause two translational parasitic motions along X and Y, which makes the working area a narrow space rather than a straight line in reality. Through the limit boundary search method, we determine the working area of the 3-PRS PM structure to be that shown in Fig. 3. The cylindrical space is the working area necessary for the simulation. From Fig. 3, the working area required is included in the whole workplace, which means that the structural dimensions we estimated meet the design requirements.

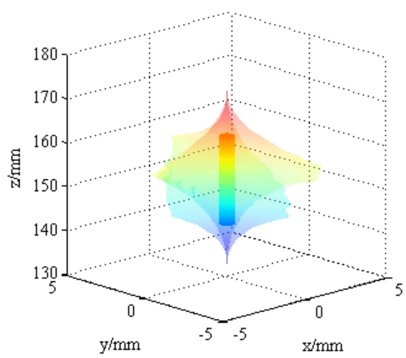


Fig. 3. Workplace of the SPMS

The 3D model of the SPMS is shown in Fig. 4. It is composed of two parts, a moving platform and a fixed platform. There is a clamp on the top of the moving platform that is used to fix an artificial spine, three ball screws, and three motors, which are combined by synchronous belts on the fixed platform. Three links combine the moving platform and the fixed platform together to construct the main 3-PRS PM. Supporting and fixed parts are added to complete the SPMS structure.

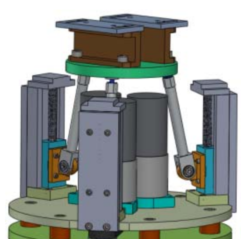


Fig. 4. 3D model of SPMS

B. Modeling of Spinal Physiological Motion

In spinal surgery, patients breathe with the assistance of ventilators, which have five typical flow waves: the exponential decreasing wave, square wave, linear increasing wave, linear decreasing wave, and sine wave [9], which are shown in Fig. 5. Among the five typical flow waves, the square wave and linear decrease wave are most commonly used in ventilators. In the flow wave, the upside indicates inspiratory breaths while the downside indicates expiratory breaths.

A normal adult breathes 16-20 times per minute, with a tidal volume of approximately 500 ml [10]. For patients of varying ages and body sizes, the parameters of the ventilator are adjusted to provide the most suitable respiratory level. Therefore, we will also set different frequencies, amplitudes and overturning angles when we use the SPMS.

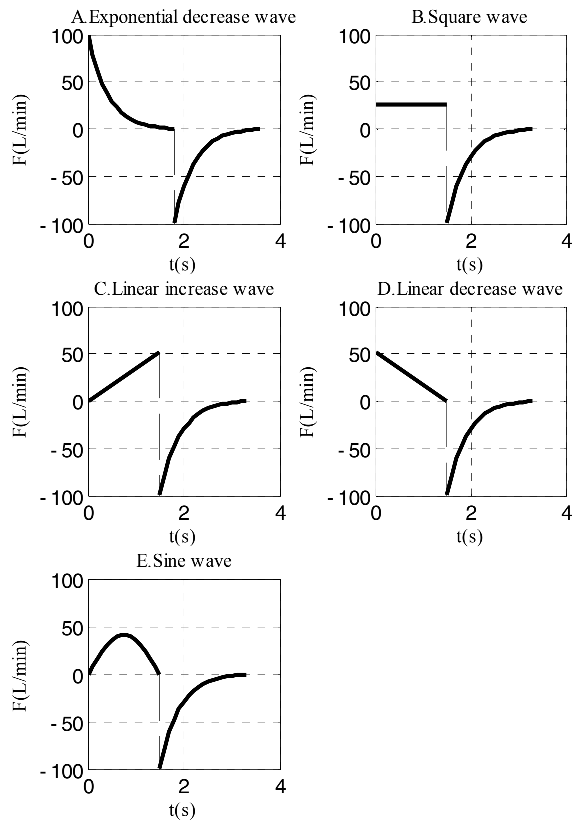
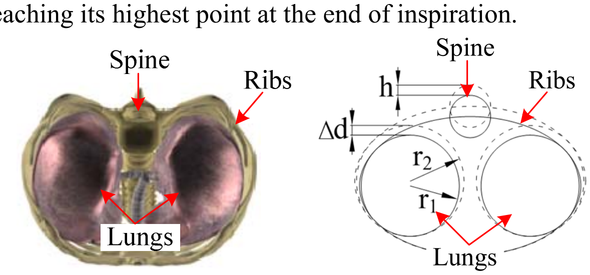


Fig. 5. Five typical flow waves of ventilators

Fig. 6 shows the respiratory modeling of the lungs. As a human being breathes, the lungs get inflated. Thus, in the theoretical geometry model, the lungs are presented as cylindrical model that expands its radius, but not its length, during inspiration. The patient lies facing the ground during the spinal surgery. The spine moves when the patient breathes, reaching its highest point at the end of inspiration.



a) Anatomical structure b) Geometry model
Fig. 6 Respiratory modeling of the lung

Assuming that the tidal volume of the ventilator is V, we obtain,

$$\frac{V}{2} = \pi(r_2^2 - r_1^2)l \tag{4}$$

where l is the length of the lung. After simplifying,

$$\begin{aligned} V &= 2\pi l(r_2 + r_1)(r_2 - r_1) \\ &= 2\pi l(2r_1 + \Delta r)\Delta r \\ &= 2\pi l(2r_1\Delta r + \Delta r^2) \\ &\approx 4\pi l r_1 \Delta r \\ &= 2\pi l r_1 \Delta d \end{aligned} \tag{5}$$

This means the position of the spine is proportional to the volume of the ventilator.

$$h = \Delta d \propto V \tag{6}$$

Next, we derive the relationship between the altitude of a spine and time, based on the square flow wave, which is used most in experiments. The average value of a normal adult's respiratory frequency, 18 times per minute, is chosen as the modeling parameter. In the square wave, the flow stays constant during the inspiratory stage and decreases exponentially until the end of the cycle during the expiratory stage. According to the properties of the square wave in Fig. 5, $F(t)$ can be expressed as,

$$F(t) = \begin{cases} b & 0 \le t \le 1.5\text{s} \\ -a^{-t+t_0} + y_0 & 1.5\text{s} \le t \le \dfrac{10}{3}\text{s} \end{cases} \tag{7}$$

The tidal volume $V(t)$ can be obtained by integration of the flow wave. The tidal volumes during inspiratory and expiratory are equal, so the whole tidal volume of a respiratory cycle is zero.

$$V(t) = \begin{cases} \dfrac{1300t}{3} & 0 \le t \le 1.5\text{s} \\ 26556 \times 11.36^{-t} + 19.60t - 73.35 & 1.5\text{s} \le t \le \dfrac{10}{3}\text{s} \end{cases} \tag{8}$$

Among the passive respiratory of a human being, the amplitude of the SPM is approximately proportional with the tidal volume.

$$h(t) = kV(t) \tag{9}$$

Therefore, we can obtain the altitude of a spine,

$$h(t) = \begin{cases} \dfrac{10t}{3} & 0 \le t \le 1.5\text{s} \\ 204.28 \times 11.36^{-t} + 0.15t - 0.56 & 1.5\text{s} \le t \le \dfrac{10}{3}\text{s} \end{cases} \tag{10}$$

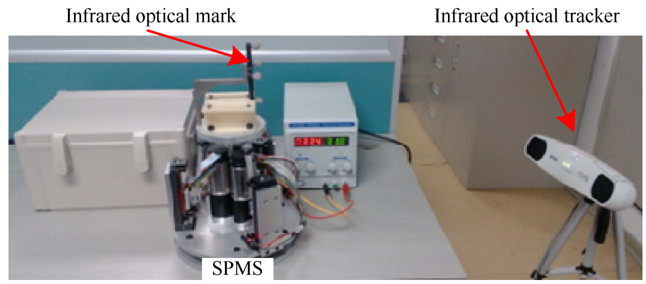
This is the drive equation of the moving platform. During the inspiratory stage, the spine altitude increases linearly to the maximum ending, and then decreases exponentially to zero during the expiratory stage.

IV. EXPERIMENTS

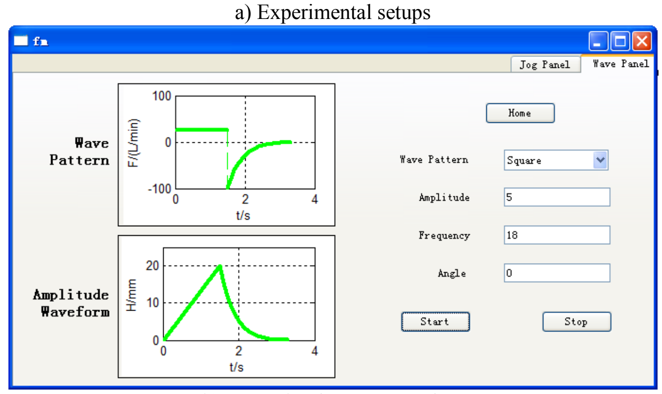
This section has two subsections. One details the SPM simulation experiments to evaluate the SPMS. The other describes respiratory motion compensation experiment using the proposed method based on WFLC on a 3-axis Cartesian robot.

A. *Spinal Physiological Motion Simulation*

Fig. 7a shows the validation experiments for the SPMS. An infrared optical mark fixed on the movement platform of the SPMS, and an infrared optical tracker (NDI Polaris®) can record the position of the SPMS by tracking the marks. Fig. 7b shows the control software of the SPMS, which provides five control waves due to the aforementioned five flow waves of ventilators.



a) Experimental setups



b) Control software GUI of SPMS

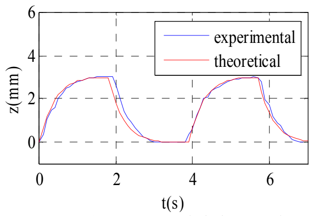
Fig. 7. SPM simulation experiments of SPMS

We divide the experiments into five groups due to the five flow waves. For each group the amplitudes are set to 3 mm, 4 mm, and 5 mm. Fig. 8 shows the comparisons between theoretical physiological curves and the actual experimental curves in different groups of flow waves.

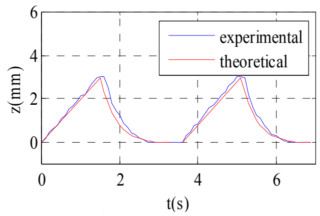
From Fig. 8 one can see that the experimental curves fit the theoretical curves well, although some errors still exist. The General Correlation Coefficient (GCC) [11] is used to evaluate the similarity of the experimental curves and the theoretical curves in different simulation parameters. Its formula is as follows,

$$R_c = \frac{\sum_{i=1}^{n} (\mathrm{y}_i - \bar{y})(\mathrm{z}_i - \bar{\mathrm{z}})}{\left[\sum_{i=1}^{n} (\mathrm{y}_i - \bar{y})^2 (\mathrm{z}_i - \bar{\mathrm{z}})^2\right]^{\frac{1}{2}}} \tag{11}$$

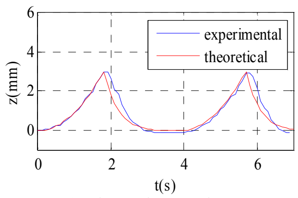
where y_i are the discrete points on the experimental curve, and z_i are the discrete points on the theoretical curve. Table 1 shows the calculated GCC between the experimental curves and the theoretical curves in all experimental situations. The accuracy of the simulated SPM has a decreasing trend due to the rising of motion amplitude; and in all experiments, the SPMS has a high accuracy more than 98%.



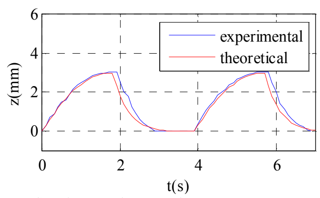
a) Exponential decreasing wave



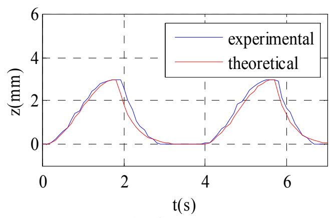
b) Square wave



c) Linear increasing wave



d) Linear decreasing wave



e) Sine wave

Fig. 8. Comparison between experimental and theoretical curves

Table 1. ERROR ANALYSIS BY GCC

Amplitude z(mm)		3	4	5
GCC R_c	**Exponential**	0.9895	0.9886	0.9877
	Square	0.9878	0.9874	0.9850
	Linear increasing	0.9863	0.9854	0.9842
	Linear decreasing	0.9871	0.9852	0.9832
	Sine	0.9886	0.9872	0.9855

B. Respiratory Motion Compensation

To demonstrate the effectiveness of the proposed respiratory motion compensation method in this paper, bone milling experiments are performed. The experimental setups are shown in Fig. 9. Bones of pig are used as test samples and fixed on the moving platform of the SPMS to simulate the operation object. A 3-axis Cartesian robot holding a bone drill is used to perform the milling operation. The diameter of the spherical drill bit is 2.4 mm. Two infrared optical marks are respectively fixed on the robot and the SPMS, and the optical tracker tracks the position and motion of the robot and the SPMS.

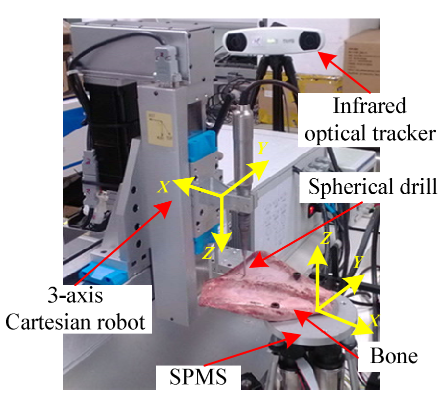
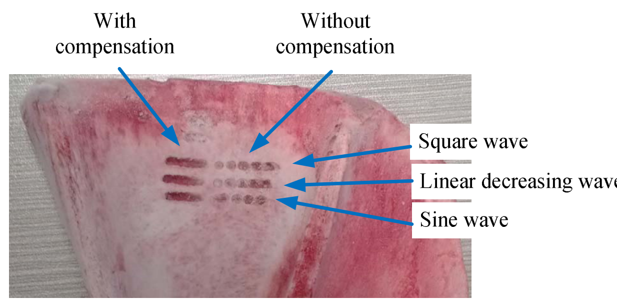
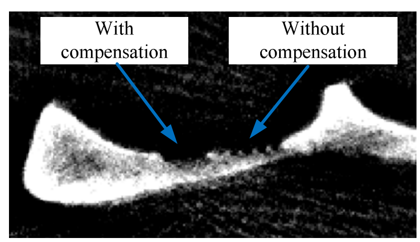


Fig. 9. Motion compensation experiment based on a Cartesian robot

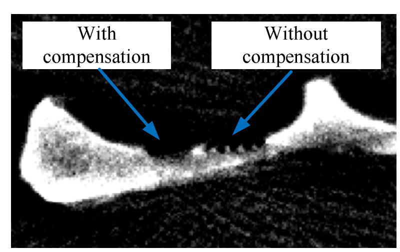
To test the performance of the compensation method with different types of respiratory motions, the SPMS simulates the motions under square wave, linear decreasing wave and sine wave of the ventilator, respectively. And three groups of bone milling operations are carried out in these situations, while in each group, the milling performances with motion compensation and without motion compensation in order to compare the performance. The milling operations are divided into two parts: firstly drill into the bone with about 2*mm* depth, secondly mill and feed along Y-axis of the Cartesian robot. The amplitudes and overturning angles of the SPMS are respectively set as 1.5mm and 2°. The overturning angles are rotated around Y-axis of the SPMS, which cause the implicated motion along X-axis of the SPMS. So the robot has to compensate the respiratory motion around Z and X axes of the SPMS.



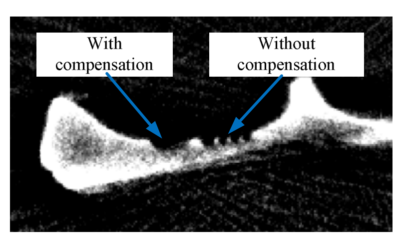
a) Top view of the milled paths



b) Transverse view in the group of square wave



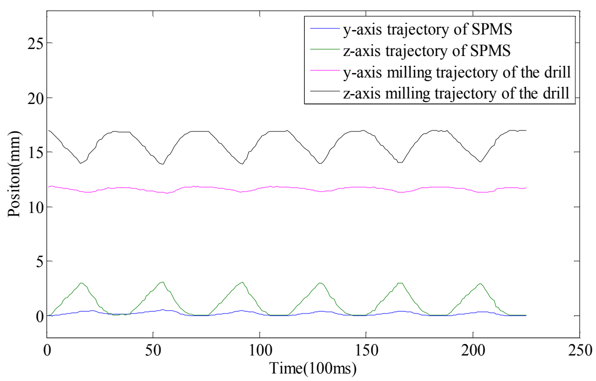
c) Transverse view in the group of linear decreasing wave



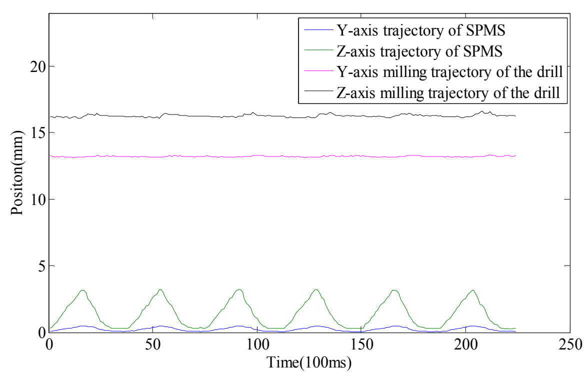
d) Transverse view in the group of sine wave

Fig. 10. The results of bone milling experiments

Fig. 10 shows the milling performances with motion compensation and without compensation. Fig. 11 shows the trajectories of the SPMS and the relative motion of the drill on the object bone in the group of square wave, while Fig. 11a shows the compensated milling and Fig. 11b shows the non-compensation milling. Without motion compensation, the milling was operated in an unstable circumstance which made the milling trajectories of the drill in Y and Z axes fluctuate significantly and the milling performance looks like holes in a line. With motion compensation, the milling trajectories of the drill in Y and Z axes are much straighter with standard deviations 0.0369*mm* and 0.0929*mm* and the milling performance exhibited as a smoother groove. In spinal surgery, the milling operation should be stable and accurate. The use of the proposed respiratory motion compensation method improved the milling operation greatly compared to the case without compensation.



a) Milling without compensation



b) Milling with compensation

Fig. 11. Compensation performance of WFLC

V. Conclusion

To research the respiratory compensation control algorithm, a SPMS that could simulate the physiological motion of the spine due to respiratory movement is developed in this paper. The structure of the SPMS was designed according to the DOF of the simulation movement. The simulation movement requires a translational movement along the vertical direction and a rotational movement around a horizontal axis. Considering the control accuracy, load capacity and function transformation of the future simulator, a 3-PRS PM was chosen as the main structure. The flexible working area of the 3-PRS PM was analyzed according to the design requirements and determined the dimensions of the structure. In spinal surgery, patients breathe with the assistance of ventilators, so the SPMS can follow the regulation of the five typical flow waves of a ventilator in surgery. Respiratory simulation experiments showed that the SPMS has a high accuracy of more than 98%.

For the compensation of SPM, an algorithm that can be used in the robotic system to execute active compensation is proposed in this paper. The compensation algorithm is based on WFLC, which can adapt to variation in the frequency and amplitude of a quasi-periodic signal. We carried out respiratory motion compensation experiments on a 3-axis Cartesian robot with the SPMS, using bone milling operations to test the proposed performance of the respiratory motion compensation algorithm, and the comparison results between compensated and non-compensated operations show that it can significantly improve the performance in bone milling and had the potential to be used in other operations of spine surgeries.

References

[1] J. Gangloff, R. Ginhoux, M. de Mathelin, L. Soler, and J. Marescaux, "Model predictive control for compensation of cyclic organ motions in teleoperated laparoscopic surgery," *IEEE Transactions on Control Systems Technology,* vol. 14, pp. 235-246, 2006.

[2] G. B. Chuang, S. Kim, S. G. Lee, B. Yi etc, "An image-guided robotic surgery system for spinal fusion," International Journal of Control, Automation and System, Vol. 4, pp. 30-41, 2006.

[3] K. H. Wong, J. Tang, S. Dieterich, H. Zhang, T. Zhou and K. Cleary, "Respiratory motion compensation studies using a 3D robotic motion simulator and optical/electromagnetic tracking technologies," Nuclear Science Symposium Conference Record, Vol. 4, pp. 2652-2655, 2004.

[4] M. C. Cavusoglu, J. Rotella, W. S. Newman, S. Choi, J. Ustin, and S. S. Sastry, "Control algorithms for active relative motion cancelling for robotic assisted off-pump coronary artery bypass graft surgery," in *Proceedings of 12nd International Conference on Advanced Robotics(ICAR 2005)*, Seattle, WA, 2005, pp. 431-436.

[5] C. Riviere, A. Thakral, I. Iordachita, G. Mitroi, and D. Stoianovici, "Predicting respiratory motion for active canceling during percutaneous needle insertion," in *Proceedings of 23rd Annual Conference of the IEEE Engineering in Medicine and Biology Society, IEEE*, Istanbul, Turkey, 2001, pp. 3477-3480.

[6] W. T. Ang, M. Krichane, and T. Sim, "Zero phase filtering for active compensation of periodic physiological motion," in *Proceedings of 1st IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, Pisa, Italy, 2006, pp. 182-187.

[7] A. Thakral, J. Wallace, D. Tomlin, N. Seth, and N. V. Thakor, "Surgical motion adaptive robotic technology (SMART): Taking the motion out of physiological motion," in *Proceedings of 4th International Conference on Medical Image Computing and Computer-Assisted Intervention(MICCAI 2001)*, Utrecht, Netherlands, 2001, pp. 317-325.

[8] B. Widrow and S. D. Stearns, "Adaptive signal processing," *Englewood Cliffs, NJ, Prentice-Hall, Inc., 1985, 491 p.,* vol. 1, 1985.

[9] Q. Zhang, "Quality Control Testing Technology of Ventilators and Anesthesia Machines," ed. Beijing: Chinese Metrology Publishing House, 2010, pp. 73-74.

[10] W. Liu and L. Shao, "Respiratory System," ed. Shanghai: Shanghai Jiao Tong University Press, 2012, pp. 38-40.

[11] S. zhang and J. Lv, "Discussion about correlation coefficient," *Mathematics in Practice and Theory,* pp. 102-107, 2009.