DEVELOPMENT OF A WEARABLE ROBOT FOR ASSISTING CARPENTRY WORKERS

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Abstract: The work of fitting ceiling boards is one of the hardest in carpentry, as it requires large muscular power. Hence there is a need to develop assisting apparatus for such work. In order to use this apparatus anywhere a wearable robot is the most suitable. As the robot must be autonomous and lightweight a design requiring low power is proposed. A semi-active control method has been developed using springs, that requires low energy but satisfies the requirements of compliance and assistive force. In this paper several aspects of design, control and experiments of the developed prototype is explained. The experimental results prove that the robot reduces the muscular fatigue of carpentry worker by providing suitable assistive force.

Keywords: wearable robot, carpentry work, semi-active device

1. INTRODUCTION

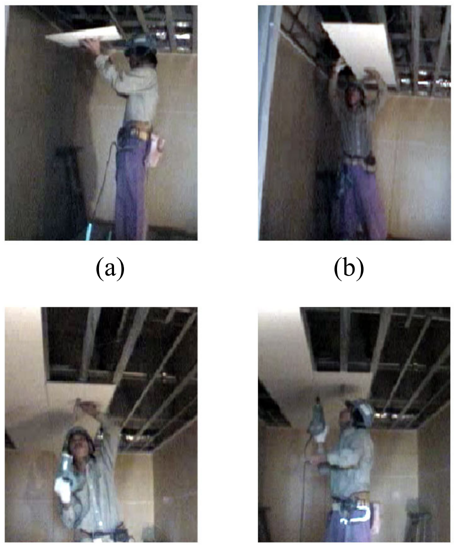
The average age of a carpentry worker has been going up due to the impact of falling birthrate and an aging population. As the muscular power of a worker decreases due to age, the worker's load carrying capacity decreases. Fitting ceiling boards is one of the hardest jobs in carpentry and there is a need to develop assistive apparatus for such jobs. Several apparatus for helping workers already exist, but most of them cannot be used in messy construction sites. Therefore, the need for developing assistive apparatus in the form of a wearable robot is of great importance.

The reason why this type of carpentry work is harder than other jobs is because there are several phases in one task as shown in Fig.1.

(a) Lifting up of board
(b) Setting the board with both hands in proper plane
(c) Support the board with one hand and fix the screw
(d) Leave the board and fix the screw with one hand

In particular, phases (b) and (c) are the hardest of the four phases. Workers have to support a board overhead and maintain the supporting posture for a long time. The muscles become tired as the worker perform this task repeatedly without any rest. A robotic device for assisting these phases can reduce the workers muscle fatigue efficiently. It is important that phase (a) requires dynamic motion and (d) needs a quick and accurate positioning. It is necessary to make all these motions possible when workers use the robot.

These observations led us to decide the essential requirements: we have to make a wearable robot that is specialized for a man supporting boards and it should allow for precise motion.



(a) (b) (c) (d)

Fig.1 (a)-(d) Different phase of the task

2. CONCEPTUAL DESIGN

2.1 Previous work

A number of different methods have been proposed in developing assistive robots or apparatuses in the last few years. Several wearable robots are shown in [1]. Non-wearable robots are shown in Herder [2]. The main aim of the device is assisting patients who have neuromuscular diseases and cannot move their arms using their own muscular power. These apparatuses are normally fixed on the side of wheelchairs and support the patients arm. In particular, Herder's [2] method is interesting since it can deliver the force to a forearm. It has two tension springs and these springs generate a constant upward force when patients move their arms. As a spring has the property of energy conservation, electric power is not required, and only fine-tuning of the spring constant is required. Although this method has several benefits, it is not possible to change the applied force easily. Therefore, if the generated force could be changed and all the benefits are still possible, it would be most suitable for assisting carpentry work.

2.2 Basic design

In order to tap the benefits using of springs and to change the generated force easily, we propose a semi-active method of control. One of the characteristics of the proposed method is the use of two springs. In the previous works [2] as shown in Fig.2, all springs are tension springs, but our model uses a tension and a compression spring. When a compression spring (free length = L m, spring constant = k_c N/mm) set at (0, 0) and tension spring (free length = 0 m, spring constant = k_t N/mm) set at (0, y_t) are bonded at the free end, the resultant force is expressed as follows:

$$T_x = \{-(k_c + k_t)r + k_c L\}\cos\theta \tag{1}$$

$$T_y = \{-(k_c + k_t)r + k_c L\}\sin\theta + k_t y_t \tag{2}$$

This equations show that when r (length from origin to bonded point) is as given in Eq.(3), the resultant upward force is constant where $T_y = k_c y_t$, and horizon direction resultant force is zero where T_x=0.

$$r = \frac{k_c L}{k_c + k_t} \tag{3}$$

Due to this, the resultant force only acts towards the upper side (Fig.3). Although this is true only when r is as given in Eq. (3), the resultant forces mainly acts upward as shown in fig.4. This force is applied to the forearm and it is used for reducing the loading force on the arm due to the boards.

In order to apply this force, a pantograph mechanism is used. This mechanism changes the force based on a magnification ratio. As shown in Fig.5 the force input at point A is output as a force at point B in the rate of $1/L_{pan}$ in magnitude. In our method, the forces generated by the springs is input at point A and delivered to the forearm at point B.

In addition to these, it is necessary to change the force in order to operate an active device. Equation (2) shows that when we want to change T_y we have to adjust the height of the tension spring y_t, because the other parameter does not change. Therefore, a semi-active device is added as shown in Fig.6. The semi-active device consists of a motor, a ball screw, a linear motion guide and a tension spring the end of which is bonded on the base. In order to change the spring height (y_t) the motor is activated to move the ball screw. On the contrary, when we want to maintain the force, we have to stop the motor and this does not require high power. In the support posture, the supporting force needed is constant,

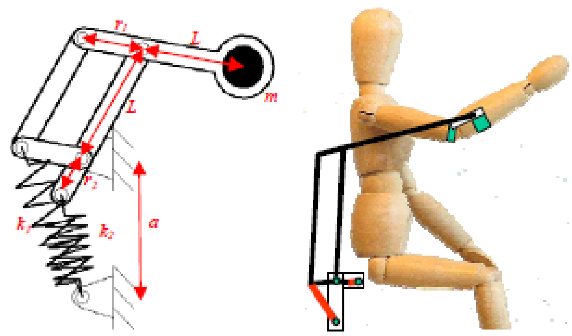


Fig.2 ARMON[2]

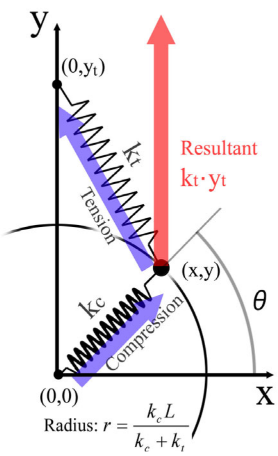


Fig.3 Spring force

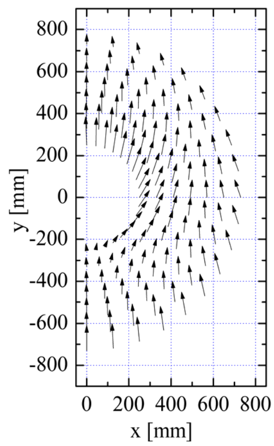


Fig.4 Calculated resultant force

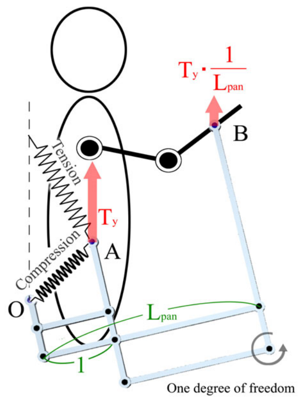


Fig.5 Pantograph

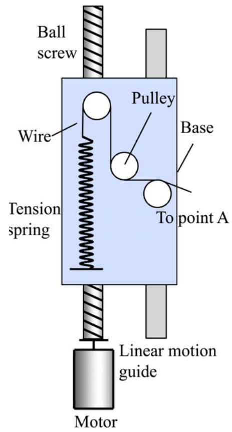


Fig.6 Semi-active device

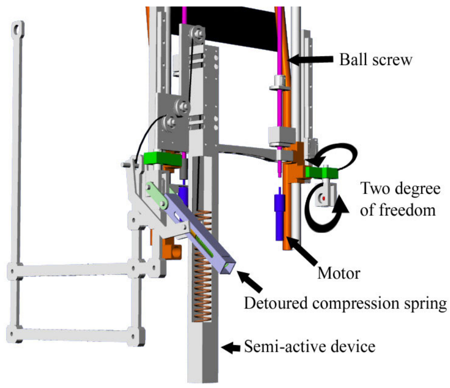


Fig.7 Basic design of the wearable robot

and using the semi-active device requires low energy consumption. In addition, the usage of springs has another benefit as it provides compliance. This compliance gives the workers good mobility that is necessary for accurate and delicate tasks like setting the boards in proper position and fixing the screw. Figure 7 shows the basic design of the wearable robot.

3. PROTOTYPE SPECIFICATION

3.1 Design details

The first prototype was made and analyzed as shown in Fig.8. Figure 9 is a vector diagram showing the influence of the effect of pantograph. It shows the magnitude of vectors if y_t = 210 mm. The size of robot is made considering the average height of a Japanese man. Table 1 lists the specifications of some parts of the developed prototype. The total mass is a little heavy because the prototype gives priority to strength. There exist possibilities to reduce the weight of the robot and to make it much smaller.

3.2 Force, energy and mobility-considerations

The generated force at point B in Fig.5 is measured and compared with the calculated force. Some examples of the force are shown in Table 2. The design was successful because the force values are nearly the same. It is assumed that small differences in each value are due to a little difference in position when we measured or due to interference of metals and wires. The maximum Force to which this device can be output is 4.5 N.

The adjustment speed of the force was also measured. The maximal adjusting force per second is 11.24 N/s. If we want to make this a little faster, we can choose a more powerful motor.

Energy consumption was also checked. When the motor is stopped, it needs an average of 3.75 W. If we move the base up and down, the motor needs 28.8 W and 1.2 W respectively. As an example, the base is moved up three seconds and kept 24 seconds there. After that, in another three seconds the base is moved down. In this case, the average electricity consumption is 6 W. This clearly shows that this robot needs a small amount of energy consumption and hence does not need a big battery.

Observing the operation area by using motion capture camera, it was shown that the robot has enough work area for the required job. In addition, assisting the forearm does not affect the wrist, hence the robot does not disturb accurate positioning.

4. MEASUREING EFFECTIVENESS

An experiment was performed for measuring the effectiveness of the designed robot. In the experiment, electromyogram (EMG) of a subject who maintained a three kilogram board as shown in Fig.1-(a) was measured. He kept the posture for 130 seconds and his EMG was measured for intervals of 10 seconds after beginning, 60 seconds and 120 seconds later. To show the difference between assisted performance and not assisted, we focus on the range of 120 to 122 seconds and show the difference in Fig.10 (using the robot) and Fig.11 (not using the robot). Measured points are the flexor muscles of the forearm (drawn with red in Fig.10 and Fig.11), biceps brachii muscle (blue) and deltoid muscle (green). Comparing Fig.10 with Fig.11, all of the waveforms in Fig.10 is smaller than in Fig 11. Deserving special mention is the deltoid muscle, where it was found that the subject felt much less tiredness in comparison.

When we want to see the difference of each characteristic easily, checking the waveform directly is good. In addition, when we want to judge it quantitatively, integrated electromyogram (IEMG) [mV･s] is often used (shown in Table.3). One way to survey the muscle fatigue is to check the IEMG magnitude. It shows that when muscle has fatigue, the size of EMG is bigger. Therefore, IEMG shows a transition of the level of muscle fatigue. Checking the Table 3 shows that level of some IEMG is increasing as time passes, where as in case of not assisted ones the signals are especially large. However, the brachii muscle's data does not show any effect. It is because the muscle load is often affected by the angle of joint sensitively. the mean power frequency (MNF) is usually used [3]. It is calculated as follows;

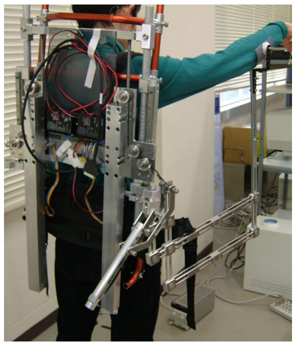


Fig.8 Prototype

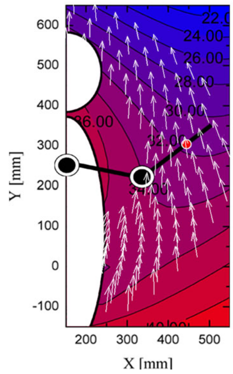


Fig.9 Vector diagram and contour (Contour unit is N)

Table 1 Detail of parts

	Property		Mass [g]
Motor	Torque 102.6[mNm/A]		113
Tension spring	Spring constant	1.4[N/mm]	373
Compression spring		0.9[N/mm]	25
Total			12000

Table 2 Calculated and measured force

y_t [mm]	Θ [deg]	OB [mm]	Assistant Force (calculated) [N]	Assistant Force (measured) [N]
90	0	400	13.0	14.7
150	26.5	447	21.8	20.6
150	45	565	18.9	19.6
190	9	583	27.5	26.5

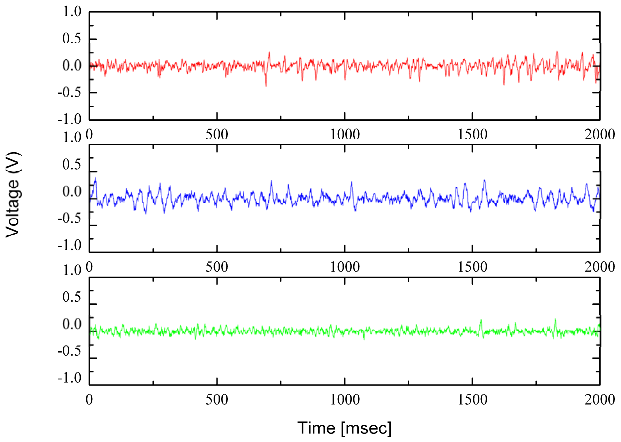


Fig.10 EMG (Assisted 120~122 s)

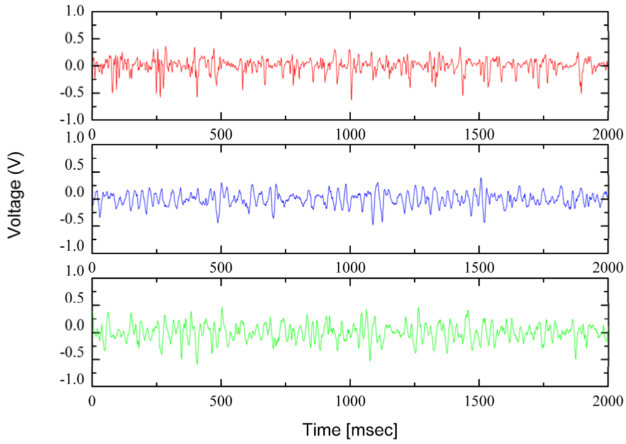


Fig.11 EMG (Not assisted 120~122 s)

Table 3 IEMG

	Time[sec]	IEMG [mV·s]		
		Flexor muscles of the forearm	Brachii muscle	Deltoid muscle
Assisted	0~10	655.05	697.55	393.15
	60~70	648.75	706.75	380.20
	120~130	681.25	646.95	356.90
Not Assisted	0~10	904.50	1193.50	915.00
	60~70	1023.10	877.60	1100.50
	120~130	1371.95	748.55	1213.45

Table 4 MNF

	Time[sec]	MNF [Hz]		
		Flexor muscles of the forearm	Brachii muscle	Deltoid muscle
Assisted	0~10	69.9	57.6	71.0
	60~70	66.7	57.0	68.1
	120~130	65.9	58.8	64.5
Not Assisted	0~10	68.1	61.8	66.4
	60~70	65.2	63.7	60.2
	120~130	60.5	54.7	53.8

$$MNF = \frac{\int_0^{\infty} f \cdot P(f)df}{\int_0^{\infty} P(f)df} \text{ [Hz]} \qquad (4)$$

Where f Hz is frequency and $P(f)$ is normalized power spectrum obtained by FFT analysis. This method uses the characteristics of muscles, i.e. as muscles get fatigued, they generate low frequency. MNF results are as shown in Table.4. This completely proves that the robot gives subjects assistive force and it works well.

5. CONCLUSION

In this paper, we propose an original method for assisting a carpentry worker to support boards and explained the developments of a prototype robot for this propose. The specification of the prototype has been evaluated. Experiments were conducted to show the effectiveness of the robot and good results were obtained. Hence energy saving design was successful, a large range of movement was obtained and compliance gave the worker comfortable mobility. Moreover, by using the robot, muscle output force is reduced and muscle fatigue was also clearly reduced.

However, these experiments only showed that this robot works for the arms. In order have better comparison, we will have to measure the effectiveness of the total energy consumption of workers. In addition, the prototype still has some problems, like large mass, low adjusting speed and large size. Therefore, we will have to develop a more practical robot. Further research will be required for realizing a more practical design. Then, the next stage is how to operate it effectively.

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