Design and Analysis of a Safe Robot Arm using Safe Joint Mechanism for Physical Human-Robot Interaction

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I. INTRODUCTION

For industrial robots, safe human-robot coexistence is not as important as the fast and precise manipulation. However, service robots often interact directly with humans for various tasks. For this reason, safety issues related to the physical human-robot interaction have become increasingly important. Although several researches for collision safety between humans and robots have been conducted [1][2][3], the intrinsic safety for the physical human-robot interaction has not been realized yet.

In this study, a novel safety mechanism based on the passive compliance, safe joint mechanism (SJM-III), is proposed. The SJM-III is composed of the passive mechanical elements such as linear springs and an inclined link mechanism. The springs are used to absorb the large collision force for safety, while the inclined link mechanism determines whether the safety feature is activated or not so that the SJM-III operates only in case of an emergency. Therefore, without compromising positioning accuracy for collision safety, both features can be achieved simultaneously with the SJM-III. Furthermore, the collision safety of the safe robot arm equipped with the SJM-III was evaluated by means of the safety criterion and the proposed collision model.

II. CONSTRUCTION OF THE SAFE JOINT MECHANISM-III

As previously mentioned, springs have been widely used in various safety mechanisms because of good shock-absorbing properties. However, a linear spring cannot be used directly in a robot arm because its displacement is proportional to the external force. A robot arm equipped with soft springs exhibits deflection due to its own weight and/or a small load, as shown in Fig. 1. This characteristic is advantageous to collision safety, but leads to low positioning accuracy. To cope with this problem, we need a spring whose stiffness remains very high when the external force acting on the end-effector of the robot arm is within the range of normal operation, but drops rapidly when the force exceeds a certain level due to collision with an object. However, no spring with this ideal feature exists. In this research, the nonlinear power transmission characteristics of the inclined link-slider mechanism which are the same as those of a double-slider mechanism are exploited to achieve this nonlinear spring feature.

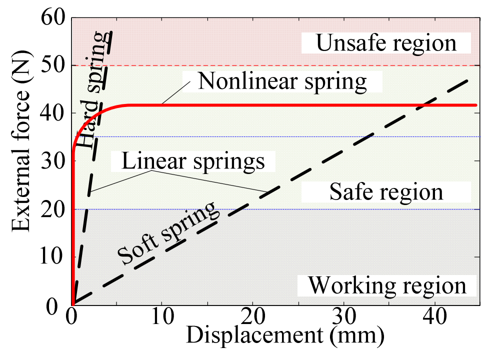

Fig. 1 Comparison between linear and nonlinear springs.

The nonlinear stiffness mechanism described above was realized in a new safe joint mechanism (SJM-III). The SJM-III consists of an inclined link, linear springs, a base plate, and a slider with rollers, as shown in Fig. 2(a). The inclined link is rotated around a shaft fixed at the base plate. The slider can translate relative to the base plate by means of a linear guide in which friction can be significantly reduced. Two rollers which contact the inclined link are arranged symmetrically so that the external torque applied in both directions can be absorbed.

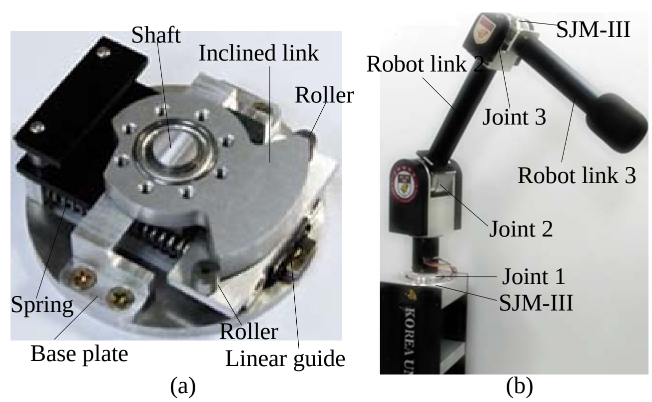

Fig. 2(a) Prototype of SJM-III, and (b) 3 DOF robot arm with SJM-IIIs.

The two prototypes of the SJM-IIIs were constructed to apply to the 3 DOF robot arm as shown in Fig. 2(b). Table I represents the detail specifications of two SJM-IIIs. The SJM-III applied to Joint 1 provides a different threshold torque according to the direction of rotation. To compensate the gravity effect of the robot link and load, the threshold

This research was supported by the Center for Autonomous Intelligent Manipulation under the Human Resources Development Program for Robot Specialists (Korea Ministry of Knowledge Economy).

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torque in the direction of gravity was set to a high value (CW).

Table I Specifications of SJM-IIIs.

Parameters	SJM-III for Joint 1	SJM-III for Joint 3
Size (mm)	ϕ80x32	ϕ70x22
Weight (g)	140	100
Threshold torque (Nm)	8 (CW) 8 (CCW)	13.5 (CW) 7.1 (CCW)

III. Analyses and Experiments for Safe Robot Arm

In order to evaluate the safety of the safe robot arm using the SJM-III for the dynamic collision, the collision analysis was conducted using the collision model as shown in Fig. 3.

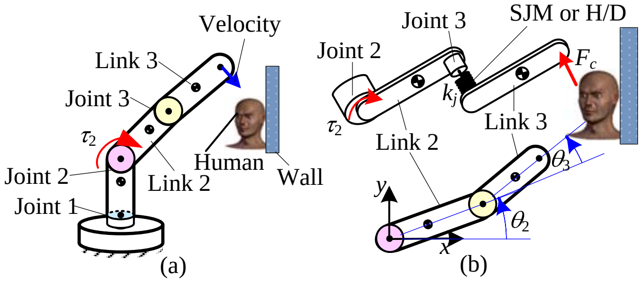

Fig. 3 Collision model between human head and robot arm. (a) Concept collision model, (b) simplified collision model.

In this analysis, I_2= 0.63 kg·m^2, I_3= 0.24 kg·m^2, m_2= 1.86 kg, m_3= 0.91 kg, l_2= 0.4 m, l_3= 0.34 m, l_{c2}= 0.34 m, l_{c3}= 0.26 m, $k_{reducer}$ = 0.71x10^4 Nm/rad, $c_{reducer}$ = 10 Nms/rad, θ_d = -90° and the initial conditions are $\theta = [90^\circ \quad 0]^T$ and $\dot{\theta} = [0 \quad 0]^T$; the collision speed between the human head and the robot link was set to 1.3 m/s.

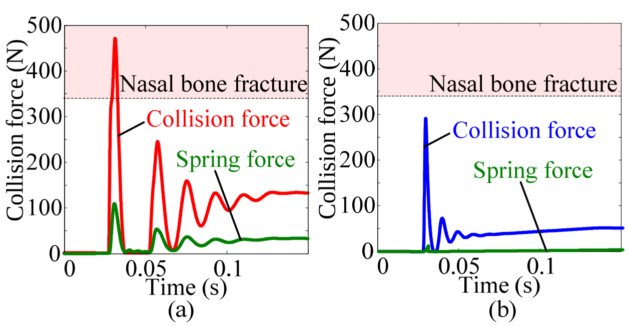

Fig. 4 Analysis results for dynamic collision. (a) Robot arm without SJM, and (b) with SJM.

In the case of the robot arm without the SJM, as shown in Fig. 4(a), the collision force reached a peak value of 490 N, and the collision force after collision was about 140N. However, when the robot arm was equipped with the SJM, the peak force decreased to 290 N and the collision force after collision also became lower than that without the SJM, as shown in Fig. 4(b). It was verified that the robot arm with the SJM provides much higher safety for physical human-robot contact than that without the SJM because the amount of the impulse with the SJM is much smaller than without the SJM.

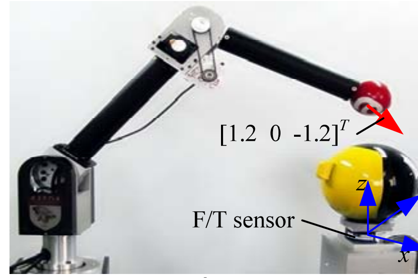

Fig. 5 Experimental setups for dynamic impact in 3D space.

Next, to verify the effect of the robot arm with SJM-III in 3D space, some experiments were conducted. The fixed wall where the F/T sensor (JR3) was installed was aligned in accordance with the *x-y-z* axis, as shown in Fig. 5. The velocity vector of the end-point of the robot arm was set to [1.2 0 -1.2]^T (m/s).

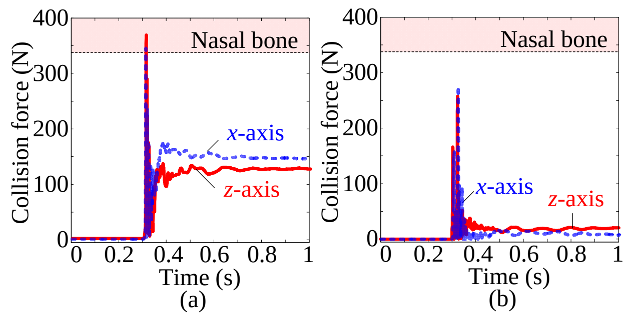

Fig. 6 Experimental results on dynamic collision in 3D space: (a) No SJM-IIIs , and (b) with SJM-IIIs.

For dynamic collision of the robot arm without SJM-III, the contact force in both *x* and *z* directions increased up to 360 N, as shown in Fig. 6(a). However, when the SJM-IIIs were installed to joint 1 and joint 3 of the robot arm, the contact force was transmitted only up to 280 N in the *x*-direction and 260 N in *z*-direction, which were below the nasal bone fracture tolerance. Therefore, the safe human-robot contact can be achieved even in 3D space using two or more SJM-IIIs at each joint.

IV. Conclusions

In this study, the third version of a safe joint mechanism (SJM-III) was proposed for collision safety. The SJM-III has smaller size, lighter weight, and lower cost than the previous SJMs. A robot arm equipped with the SJM-III can maintain very high stiffness up to a preset threshold torque, and provides a very low stiffness above the threshold.

References

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