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Development of a upper-limb exoskeleton robot for refractory construction

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ABSTRACT

In this paper, a novel 7-DOF (degree-of-freedom) upper-limb robotic exoskeleton was developed for helping refractory construction operations in furnaces. The exoskeleton is the dual-arm type wearable robot that cooperates with human operators. Each arm includes Force/Torque (F/T) sensors to detect the human's motion, and the robot can handle a refractory of up to 50 kg. The exoskeleton robot generates not only high strength but also various 3-dimensional motions with the load, and it is highly suitable for the refractory construction operation.

1. Introduction

In the steel manufacturing industry, a multitude of heavy-weight handling processes exist. For instance, various transferring operations are required for delivering final products such as thick plates, wire rods, coils, etc. as well as half-finished products such as slabs, blooms, and billets. Except for steel products, numerous weight transporting operations of ladles, pressing rolls, steel scraps, steel specimens, and so on are performed. Relatively large and heavy materials described above cannot be handled by human power, and therefore overhead cranes and forklift trucks are largely utilized.

Meanwhile, there are multiple weight transferring works that can be handled by the human strength. A representative example is the refractory construction of the converter. The work is to pile up the refractory bricks inside the converter to delay erosion from the molten steel with high temperature. A number of complicated and unstructured activities such as aligning the bricks, inserting papers between bricks, etc. are required in this process, and thus human's intelligence and sense are absolutely important. Moreover, the limited working space inside the converter does not allow large and heavy facilities to be employed. Hence, the refractory construction of the converter cannot be fully automated and depends on both worker's muscle strength and a pneumatic air-balancer, which is a rather simple facility to lift and move the refractory bricks.

Fig. 1 illustrates the structure of the converter and photographs of the refractory handling operation in POSCO. Approximately thirteen thousands of refractory bricks that weigh 25–80 kg are piled up inside of the converter. Fifteen to twenty workers are involved in the construction, and it continues for four to six days. Dozens of times of refractory construction of the converter are performed annually in POSCO.

The converter is typically comprised of bottom, body, and cone parts as shown in Fig. 1(a). During the construction, air-balancers are utilized in the bottom and the body parts of the converter whereas the human strength is used in the cone part where the bricks are relatively small and light in Fig. 1(b). The air-balancer cannot be employed in the cone part due to the interference with the inner wall of the converter. However, thousands of refractory transferring operations in the cone part cause operators' musculoskeletal pains on back, waist, and wrists. Furthermore, the latent muscular skeletal disorder caused by handling heavy-load materials for a long time may generate severe safety accidents.

Exoskeleton robots recently have been developed extensively for helping and augmenting human's muscle strength. The powered robot is a wearable type robotic exoskeleton that cooperates with human operators. The robot utilizing electric or hydraulic actuators supports or augments human muscle strength to help transporting heavy-weight objects. This reduces the physical fatigue of operators from long hour of repetitive works with heavy loads, resulting in muscular skeletal diseases.

Up to now, a variety of exoskeleton robots have been designed and implemented. The first development of exoskeleton was started by General Electric and the United States military in the 1960s as the name of Hardiman. Mosher (1967) Since then, several exoskeleton robots have been developed for a variety of purposes in many organizations. For example, XOS series by Raytheon (0000) HULC by Lockheed martin (0000) and BLEEX from Berkeley (Huang, Steger, & Kazerooni, 2005; Kazerooni, Racine, Huang, & Steger, 2005) are primarily designed with military purposes. HAL by Cyberdyne (Hayashi, Kawamoto, &

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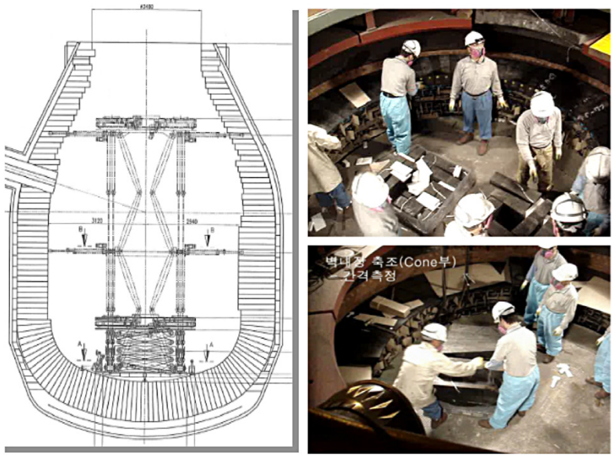

Fig. 1. Converter structure and photographs of the refractory construction.

Sankai, 2005; Kawabata, Satoh, & Sankai, 2009) and ReWalk by ReWalk robotics (0000) are developed for people with physical disabilities in heath cares. H-LEX by Hyundai motor group (Hyundai Motor Group, 0000), Daewoo Shipbuilding and Marine Engineering's exoskeleton at the shipyard (DSME, 0000), and FORTIS by Lockheed martin (0000) are the robot for industry. Nevertheless, most exoskeleton robots up to now have been focused on the military and rehabilitation purposes rather than industrial applications.

First, former exoskeleton robots were tried to apply in the refractory operation. Full-body type robots such as XOS, HAL and so on, which can manipulate refractories, were considered. The locomotion with legs like human can move well, but those platforms were vulnerable to maintain a balance against abrupt change of mass center when lifting heavy loads. Therefore, a more reliable robot mover was required instead of the leg frames.

In this paper, a novel dual-arm type upper-limb exoskeleton combined with air-balancer was developed for helping the refractory construction in the converter. Each arm includes a F/T sensor for detecting the human's motional intension accurately, and this allows to achieve delicate motions while handling weights. Moreover, various control algorithms combined with sensors enables operators to handle a refractory up to 50 kg with ease and secure their safety during the operation.

The applicability and stability of the robot system were focused to be improved for steel industry comparing to preceding robots. The upper-limb robot can be simply installed at the end-effector of the air-balancer, which is currently used in the bottom and body part of the refractory construction. By use of the exoskeleton robot, the air-balancer can be used in the cone part of the converter. In addition, the combination of the upper-limb exoskeleton robot and the air-balancer can provide safe and stable refractory transferring operation. There are no concerns for a wearer to fall down while working because air-balancer securely holds the robot and wearer, although rapid change of mass center caused by the refractory occurs.

2. Motion analysis

The motion analysis of refractory handling works was performed to determine a concept of the upper-limb exoskeleton such as joint mechanism, operational range, joint velocity etc.

In transporting a heavy object, various joints and muscles on shoulder, arms, and back in the upper body are used. The representative joint mechanism of the human's upper body reflected to the design of robotic exoskeleton is specifically constructed as shown in Fig. 2, where the mechanism consists of shoulder, elbow, and waist joints. In detail, the shoulder includes flexion, abduction, and rotation. The elbow has only flexion, and the waist has rotation, flexion and lateral flexion.

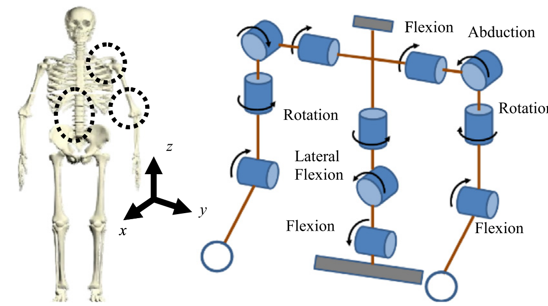

Fig. 2. Upper-body joint mechanism of the human body.

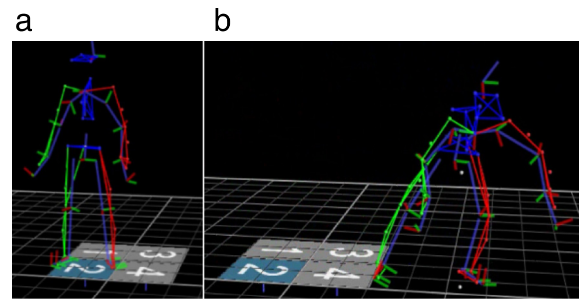

Fig. 3. Motion simulation by Vicon camera system: (a) refractory lifting and (b) transferring.

Table 1
Joint rotation angles.

Joint	Direction	Human range	Robot range
Elbow	Flexion	40–90°	60–160°
	Flexion	−10~50°	−80~70°
Shoulder	Abduction	20–90°	–
	Rotation	−60~30°	−90~3°
	Flexion	−10~30°	0–60°
Waist	Lateral flexion	−25~25°	–
	Rotation	−10~10°	–

The refractory handling operations are generally classified as several motions such as: (i) a vertical transport that lifts the refractory from low position to near waist, (ii) a horizontal transport that moves the refractory to other places in parallel with the ground, (iii) a rotation of the refractory for proper positioning, (iv) a walking motion with a refractory, (v) several other minor works such as refractory cutting, aligning, and position fixing, etc.

There are two common types of refractory moving activities. One is the horizontal transferring without moving the lower body as a short-range construction. The upper body moves to the right and left directions with waist bending resulting in generation of fast flexion and extension motions on elbows. The other is the refractory transferring with walking as a 2–4 steps distance. This includes the waist bending, but the horizontal movements of both arms are small. Hence, relatively slow flexion and extension motions on elbows are generated.

Based on the motions above, we simulated the refractory transferring operation by Vicon motion capture camera in Fig. 3 (Vicon, 0000). The refractory handling motion containing relatively large upper-body movements was considered.

As for an example of the motion analysis, Fig. 4 presents trajectories of left and right hands with respect to the waist joint. Both arms approximately move in the range of 500 mm, 1000 mm, 400 mm in x, y, z, respectively. Each joint rotation of the upper body is presented in Table 1. The result may vary depending on the operator who performs the refractory transport.