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Design of Hybrid Drive Exoskeleton Robot XoR2

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***Abstract*— The paper reports on a novel hybrid drive lower-extremity exoskeleton research platform, XoR2, an improved version of XoR. Its design concept, details of the new hardware and basic experimental results are presented. The robot is designed so that it does not interfere with the user's normal walking and supports a 30-kg payload in addition to its own weight of 20 kg. The robot has a total of 14 joints; among them six flexion/extension joints are powered. Pneumatic artificial muscles are combined with small high-response servo motors for the hip and knee joints, and arranged antagonistically at the hip and ankle joints to provide passive stability and variable stiffness. The preliminary experimental results on position and torque control demonstrate that the proposed mechanisms, sensors and control systems are effective, and hybrid drive is promising for torque-controllable, high-speed, backdrivable, mobile (but non-power-autonomous) exoskeleton robots.**

Fig. 1. ATR hybrid drive eXoskeleton Robot (XoR) Prototype 2: (Left) Front view, (Right) Side view with mannequin.

I. INTRODUCTION

To achieve exoskeleton robots useful for rehabilitation or compensation, two critical problems have to be tackled. One is how to predict human intention from various sensors and how to apply the exoskeleton force to the human body. The other is how to build such exoskeletons with limited size and weight without decreasing the motor assist capacity, i.e. the load capacity and controllability.

Although some research groups already have developed sophisticated anthropomorphic exoskeletons [1][2][3], many researchers are trying to develop new exoskeleton robots because there remain many technical problems to solve in both hardware and software aspects [4]. In fact, the achievement of a high-performance exoskeleton is still a big challenge.

Let us discuss the hardware aspect here. The robot must support human motion with appropriate torque and speed. However, it is difficult to determine how much torque and speed are required, even though the size, total power, or weight are prespecified. Once the robot structure, active/passive degree of freedom (DoF), required torques/velocities are chosen, we need to select the actuation. This is one of the most difficult parts of the exoskeleton design. It not only directly affects control performance, but also shape, weight, usability, safety and toughness, power consumption, etc. Then again, the actuator selection constrains the overall structure, DoF, and joint profiles. This design process is repeated until satisfactory performance is obtained. As such, any existing exoskeleton is just one of many possible design streams. Keeping this aspect in mind, we state the contribution of the paper in the following.

The paper proposes a non-power-autonomous exoskeleton useful for rehabilitation in some medical facilities or augmentation in some load-bearing work. Fig. 1 shows our new robot *XoR2*, the second prototype of the research platform, ATR hybrid drive eXoskeleton Robot (XoR) [5], which we will explain in detail in this paper. Instead of abandonment of power autonomy, we ask what performance can be gained from the proposed hardware. The paper describes design details on how we solve the problem of trade-off between the performance, weight and cost, and show the experimental results of the proposed system. As described below, we are especially interested in dynamic, precise torque control, backdrivability, and high speed so that the robot does not interfere with the user's motion.

The paper is organized as follows. Section II presents the design concept and target. The highlight is its novel actuation: pneumatic-electric hybrid drive, which was first proposed by Khatib [8] and Nakata [7], but first introduced to exoskleton robots by the authors [9] to obtain precise torque controllability, backdrivability, and gravity compensation (G-comp). The idea is brieflzy reviewed. Section III provides a hardware overview of the robot. Many improvements are made from the first prototype [5]. This includes mechanism, actuator, sensors and control systems. Section IV provides the experimental results to show the basic performance of the proposed hardware system. Assist control algorithms, simulations, and experiments will be presented in our future papers.

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II. DESIGN CONCEPT

A. Design target

We seek the following items as the important features of our lower-extremity exoskeleton robot.

(T1) Anthropomorphic design
(T2) Precise torque controllability
(T3) Sufficient load capacity
(T4) Sufficient motion speed
(T5) Quasi-power autonomy
(T6) Light weight
(T7) Passive backdrivability
(T8) Autonomous balancing capability
(T9) Size adjustability and wide range of motion
(T10) Modurality
(T11) Low cost (less expensive actuators and sensors)

Item (T1) and (T2) are important because we aim at torque-based assist control. Choice of anthropomorphic or non-anthropomorphic design determines how the robot is connected to the human body and the interchange of force and energy. The former leads us to joint torque-based assist control. Specifically, we apply our full-body force control framework [10] to the exoskeleton because it allows natural force interaction between the robot and external force exerted by the user.

Items (T3),(T4) and (T5) are necessary for the robot not to interfere with the user. This means that when the user does not want to be assisted, the robot must not apply any force to the user; the robot behaves as if it is not there, like a *shadow*. The idea is shared by some existing military-use exoskeleton [1][2]. Note that this requires the robot to support at least its own weight at *any* configuration. One may regard this function as a bottom line, but, this is quite challenging. Actually, no existing exoskeletons (including ours) have this property, but aiming at this goal is valuable.

Item (T6) (and in some cases (T7)) is essential for absolute safety both for user and robot when the power is suddenly cut off, while Item (T8) is useful for controlled safety. Item (T9) is necessary for any exoskeleton wearable by different users. Item (T10) is useful for researchers to test different combinations of the powered joints (assisting hip only, ankle-only, or right leg only, etc). Item (T11) is unavoidable if we want to commercialize the robot right after prototyping the research platform.

Aiming at the above design targets, we employ the hybrid drive solution, which is described below.

B. Hybrid drive solution

1) Why hybrid?: We choose hybrid because no alternative technology is available to meet Items (T1)-(T7). Direct torque control is limited to a few actuators such as a direct-drive motor (DD-motor). A DD-motor is usually too heavy to be used for robots. Torque control with torque sensor feedback is also possible, as shown in KUKA/DLR Lightweight Arm or SARCOS hydraulic robots. Both meet Items (T2) and (T3), but use stiff actuators, which is not consistent with Item (T7). Also, low-cost, compact and lightweight torque sensors are not commercially available, which contradict (T11). The hybrid drive solves this problem as follows. Note that Series-Elastic-Actuator (SEA) [6] uses conventional electric servomotors, and can be incorporated into the hybrid solution.

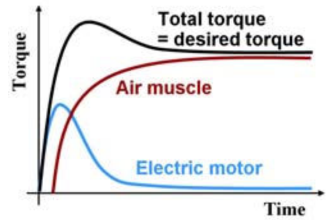

Fig. 2. Hybrid drive concept: PAMs have considerable delay and steady-state error due to the delay of the control valves and compressibility of the air. Electric motors without high reduction gear have high response, but can generate high torque for only a short period of time. The hybrid drive makes the sum of the two actuator outputs equal to the desired torque.

2) What is hybrid drive?: The conceptual illustration is depicted in Fig. 2 [5]. The purpose is to make the sum of two actuator outputs equal to the desired torque. In the lower extremity exoskeleton design, we specifically combine pneumatic artificial muscles (PAM) with 'small' electric servo motors. PAM can generate relatively large force, while their weight is light compared with conventional pneumatic cylinders. However, PAM has the same difficulty in servo control as other pneumatic actuators because of the large compressibility of air. This causes considerable delay in the force-tracking task. However, if we can introduce a high-response actuator, the delay can be reduced. Specifically, small servo motors are useful for this purpose because those without high-ratio gears are not only very fast, but also can generate high torque for a *short* period of time.

Ideas of assigning high-amplitude and low-frequency torque to the pneumatic actuators, and low-amplitude and high-frequency torque to electric motors are proposed in [7]. Moreover, hybrid drive of antagonistic PAMs and DC motor has been presented in [8] in their Macro-Mini scheme. Therefore, hybrid drive with PAMs and motors itself is not new. But, its special usage for lower-body exoskeleton or humanoid robots was first proposed by the authors [9]. Specifically, we carefully arrange PAMs so that they generate necessary force in a wide range of configurations. (Before introducing PAM, we first tried a custom-made pneumatic cylinder and obtained the similar performance.) In our lower-extremity exoskeleton robots, the most important torque control task is G-comp. Since the anti-gravitational torque becomes small when the robot is in an upright posture with the knee fully extended, we can make the best match between kinematic / kinetic configuration and force characteristics of the actuator, as illustrated in Fig. 3. The idea has been validated in experiments on the initial testbeds and the first prototype (see [5] and the accompanying video).

3) How to select each actuator?: Although some systematic analysis is possible [13], or, one can optimally compute the contribution of each actuator using nonlinear optimal

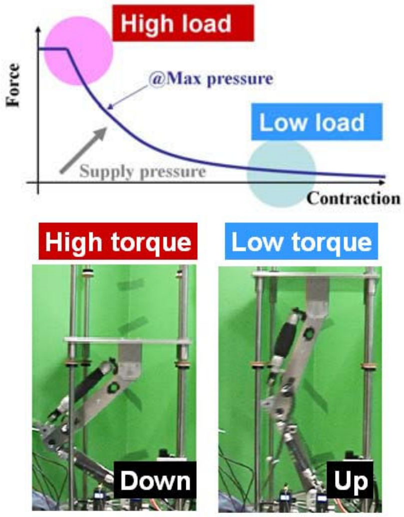

Fig. 3. Characteristics of PAM suitable for gravity compensation: (Top) PAM can generate only a small amount of force when fully contracted while it can generate large force around zero contraction. (Bottom) The idea is to arrange PAM so that this characteristic matches with the required joint torque profile [9].

control [14], we can determine intuitive and specialized criteria at the initial exoskeleton design:
(1) Maximum static torque is covered by PAMs;
(2) Dynamic torque is covered by servo motors.

Specifically, (1) indicates the anti-gravitational torque for stance support, and (2) means motion tasks such as fast swing or dynamic balancing, which can be large in a short period of time. Such torque and velocity profiles can be easily extracted from a database, simulations, or real experimental data on humans performing some motion tasks.

This intuitive assignment allows sensorless torque control. With low-reduction gear, controlled motor current is proportional to its output torque. If G-comp by PAM is perfect, sensorless torque control is possible by the motor current control. Our recommendation is to select the motors such that the *rated torque* is equal to G-comp torque for the *swinging leg*. This selection is actually verified in Section IV-A.

Moreover, if PAMs are arranged in an antagonistic configuration, one can utilize them as variable stiffness actuators. Although PAMs have considerable delay due to the control valve (not the actuator itself; PAMs are very fast and friction-free), their behavior under constant supply pressure can be well modeled (e.g. using force sensors in advance). Thus, we can expect joint torque control is possible by only measuring the angle of the joints (spring torque). Besides, torque sensing itself is an important feature of XoR2, and is described in Section III-C.

III. Hardware overview

Fig. 1 shows the overview of the new robot, XoR2. Its specifications are summarized in Table I. Fig. 4 shows the skeleton of XoR2, along with its mechanical structure and DoF configuration. It has a total of 14 joints, among them six flexion/extension joints powered as in XoR. The hip

TABLE I
XoR2 Basic specifications

Mass	w.out Valve	20 kg	w. valve	25 kg
Size	Height	165-175 mm	Width	50-60 mm
DoF	Active	6	Passive	8
Speed	Walk	> 1 m/s	Squatting	> 2 s
Payload	Walk	-	Squatting	35 kg
Pos. sensor	Active	Encoder	Passive	POT
Force sensor	Active	Custum LC	Passive	None
Sampling	Task	2kHz	Servo	10kHz

Active/Passive: active or passive joints, Pos.: position, POT: potentiometer, LC: load cell

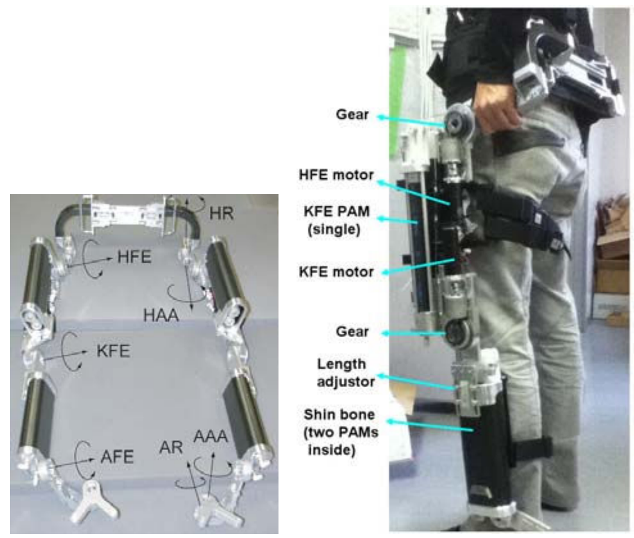

Fig. 4. (Left) Mechanical structure of XoR2: CFRP pipes are used as the main links. Antagonistic pairs of PAMs are set inside the pipes. The figure also shows the degrees of freedom (see text). (Right) Leftside view: DC motors are introduced in HFE and KFE joints. The unilateral PAM can be seen in front of the thigh link. The length of each link can be adjusted up to $\pm$30mm.

flexion/extension (HFE), knee flexion/extension (KFE) and ankle flexion/extension (AFE) joints are the active joints. The remaining joints, i.e. the hip abduction/adduction (HAA), hip rotation (HR), ankle AA (AAA) and ankle rotation (AR) joints, are the passive joints. Shoes are attached to the bottom of the robot as shown in Fig. 1. Although the same hybrid drive concept is employed, XoR2 differs from XoR in many aspects including mechanism, sensors and control systems, whose details we explain below.

A. Actuation

In the first prototype, we aimed at 100% human weight compensation. This made the robot heavy (37 kg) althoguh all the control systems are put outside of the robot (the robot is under modification [17]). This time, we reduced the weight to 20 kg excluding the valve box, and 25 kg including it. This made compromise for joint torque approximately double.

Table II shows the joint specifications, where the range of motion, range of torque and maximum velocities are indicated. Introduction of off-the-shelf actuators is consistent with Item (T11) of the design concept. For the electric actuator, a Maxon 60W DC servo motor is used (it is easy

TABLE II

JOINT SPECIFICATIONS OF POWERED JOINTS

Joint	Actuation	RoM Nm	Torque range deg/s	Max velocity deg
HFE	hybrid	-120 / 30	(-20, 60) / (-60, 20)	700
KFE	hybrid	0 / 120	(-20, 20) / (-60, 20)	700
AFE	PAM only	-60 / 40	(-10, 37) / (-37, 10)	400

See the text for joint names. Note that the maximum torques are evaluated at both ends of RoM. Maximum velocity values are valid only for the controlled case.

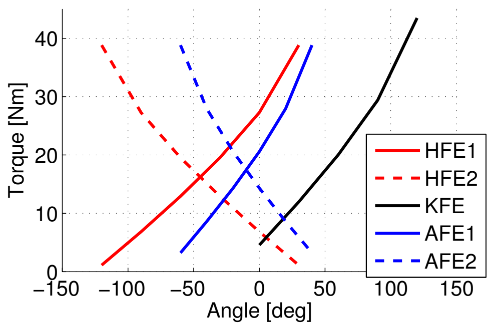

Fig. 5. Theoretical output torque by PAMs. See also Table II.

to replace with 200W brushless DC servomotors used in XoR; the maximum joint torque is increased to 100 Nm). To avoid interference with the user, we arranged the motor perpendicular to the joint axis using a bevel gear, which was not the case with XoR, where the motors are arranged parallel to the joint axis using timing belts.

For the pneumatic actuator, *ten* FESTO DMP20 muscles are used (for the previous version, *six* DMP40 muscles were used). This can generate contraction force up to 1500 N. Radius of the pulley is 60 mm for HFE and AFE joints, and 50 mm for the KFE joint. The length of the PAM is 250 mm and 180 mm resp. The theoretical output torques by PAMs are plotted in Fig. 5.

XoR2 has antagonistically driven joints at the hip and ankle. This is in contrast to XoR, where PAMs were arranged in unilateral configuration to reduce the weight [5]. It is well known that an antagonistic pair of PAMs generates not only bidirectional joint torque, but also controlled stiffness around an equilibrium point. This facilitates the passive stability, or periodic motion control.

As shown in Table II, an antagonistic drive with two PAMs is employed only on the HFE and AFE joints, and electric motors are introduced only on the HFE and KFE joints. It should be noted that initially we tried to introduce antagonistic and hybrid drive for all the powered joints, but eventually came up with this compromise of a combination. One reason for this combination is that dynamic torque is required at hip and knee joints more often than at ankle joints. The explanation lies in human balancing, where a human utilizes joint stiffness at the AFE joints by co-contraction of the muscles. In [12], this local reflex control is called ‘Ankle Strategy’, whereas more advanced, demanding control by the central nervous system is called ‘Hip Strategy’,

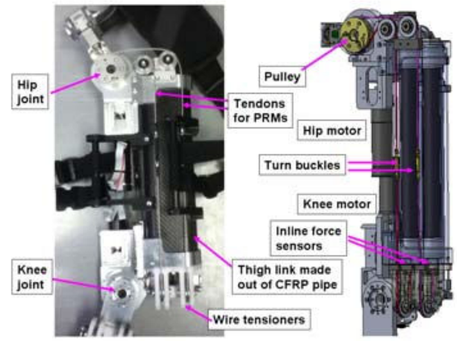

Fig. 6. Arrangement of the two PAMs, tendons, force sensors for the hip joint. (left) Inner side view of the actual mechanism, (right) CAD model.

where fast and precise joint torque control is necessary for HFE joints (and upper body joints). We are planning to test this balancing controller, as we did in a life-size biped humanoid robot [15]. The other reason is that knee joints should almost always apply extension (anti-gravitational) torque when standing, and we can resort to gravity or motor torque for flexion.

B. New mechanism

Much effort has been done in re-designing the mechanisms for the hybrid drive joints. To make the robot lightweight, carbon fiber reinforced plastic (CFRP) pipe is employed as the main structure, inside which PAMs are installed. Fig. 6 shows how the PAMs and tendons are arranged. The two PAMs of HFE and AFE are set inside of the CFRP pipes. The wire is coming from the bottom side of the pipe, turned around a tensioner, drawn to the top side of the pipe, then fixed to the pulley at the joint. The pulley is fixed to the gear for the motor. Simple wire tensioners made from plastic are introduced to prevent the tendons from loosening out of the pulleys. For the inline force sensors, see Section III-C.

Why did we choose this relatively complex design? This is because of Items (T9)(T10). This configuration allows us to use longer PAMs, thus allowing a wider range of motion (RoM) of joints to cover both squatting and walking. The link length can be adjusted by long holes and screws, and so can the wire accordingly (small turn buckles are used). As a result, the robot can fit a human of 165-175 cm in height.

Moreover, thanks to its actuator arrangement, the robot has high modularity (Item (T11)) as follows. By removing the links, the robot can be used as a hip-only assist device, or hip-and-knee assist device. For the latter case, if PAMs are further removed and a battery is installed, the robot can be made fully autonomous, and the expected weight is 15 kg. The lower limb including ankle joint and foot can also be separated out and can be used for pneumatic ankle assist devices. Otherwise, we could introduce biarticular muscle. The configuration can be changed easily by researchers. This modularity makes our robot useful as a research platform.

Unfortunately, we could not introduce miniature high-speed servo-valves up to now. The valves are under development by a company, and we tentatively applied low-cost

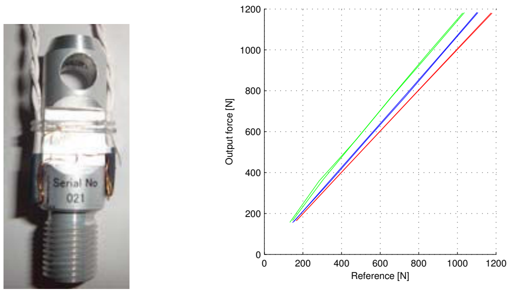

Fig. 7. (Left) Inline tension sensor (Right) Calibration results for three sensors

pressure regulators in the preliminary experiments such as G-comp and simple balancing. This caused the valve unit to be 5 kg in weight, totally 25 kg. If this weight is not acceptable, the valve unit can be put near the robot. Note, however, that the user must still apply all AA joint torque when lifting one leg because the hip AA joints are not actuated. We tried to make the hip AA active, but eventually abandoned this goal because of the size, weight and time limits. This remains as one of the main limitations of XoR2.

Finally, the robot has a pad and straps to couple the exoskeleton thigh and shank to those of the user. The pad is made out of a thin hard plastic plate and thick soft urethane pad. The position and radius of the pad, as well as the strength of the coupling, can be adjusted easily.

C. Force sensing

Estimation of human motion intention and effort is crucial for an exoskeleton robot. Force sensing is particularly useful because the robot interchanges force with the user. In addition to this main purpose, hybrid drive needs the force sensing to maintain good torque controllability. That is, contraction force of PAMs is to be measured as described in Section II-B.

Since no commercial miniature force sensors are available, we fabricated small custom-made inline force sensors. This is the strain-gauge type and can be directly connected to the micro controller Section III-D. The calibration result is also depicted in the figure. Abscissa shows the output of the high-precision off-the-shelf tension loadcell, while the ordinate shows that of the fabricated sensor. It can be seen that not only the bias but also the scale are different from sensor to sensor. From this result, we can confirm these custom-made miniture sensors can be used to measure the force applied to PAMs as long as the repeatability is preserved.

Recall that in Section II-B, sensorless torque control is discussed as a feature of the hybrid drive. Alternatively, one can actively utilize the motor to compensate for the delay of the PAMs and keep the high torque until the PAM torque catches up. For this purpose, torque error must be measured to know how much torque should be compensated. This idea has already been proposed in [8]. Although this method is sensitive to the quality of force sensor feedback, precise torque control is possible in principle.

In addition to force sensors, we are also fabricating some compact surface EMG sensors. EMG and force measurement results with/without assist control are reported in our future paper.

D. Control system

The other significant change from the first prototype is the new control system. The system architecture is motivated by Cheng's work [16]. Fig. 8 shows the on-board servo controllers attached to the backbone of the robot. In total, six controllers are developed. We introduced a Microchip 16-bit dsPIC for MPU. Using the software libraries, 16-bit floating point arithmetic instruction is possible, which is powerful enough for low-level servo control for a single hybrid drive joint.

The controller has 3ch DA output. For example, the HFE controller commands pressure to the two valves (for two PAMs) and current to the DC driver. The joint angle is measured by a rotary encoder attached to the motors (HFE/KFE) or joint (AFE). A 32-bit counter is installed for this purpose. Other passive joints are installed with analog potentiometers. The controller has 2ch differential amplifiers to measure the strain of the force sensors. Also, there are two additional analog inputs installed to measure the EMG signal from the amplifiers under development. In total, 5ch AD inputs including POT interface are available. The controller has a 100-Mbps Ethernet interface, and communicates with the host PC with one cable. The communication speed between the controllers and PC depends on the communication software and buffer size. Currently, we have succeeded in stable real-time 500-Hz communication for all I/O signals for ten servo controllers. Using this new system, a massive cable has been replaced with one Ethernet cable and one DC electricity cable.

The servo controller has a DSP (digital signal processor) specialized for fast multiplication/summation instruction. We utilize this for analog sensor filtering. Currently, all of the necessary control commands are processed in the host PC. Therefore, the onboard controllers have nothing to do except for the I/O signal conditioning including filtering and motor current measurements, and communication via Ethernet.

Precise and efficient hybrid servo drive is the important engineering work. We believe the high-speed servo valve encompasses the usefulness of the new digital controller. That is, high-performance local feedback control considering

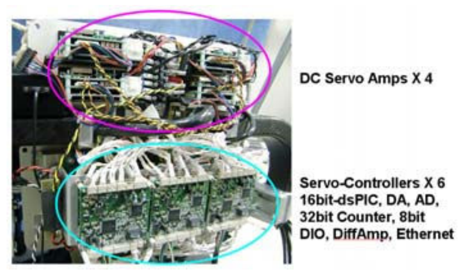

Fig. 8. Motor drivers and servo controllers

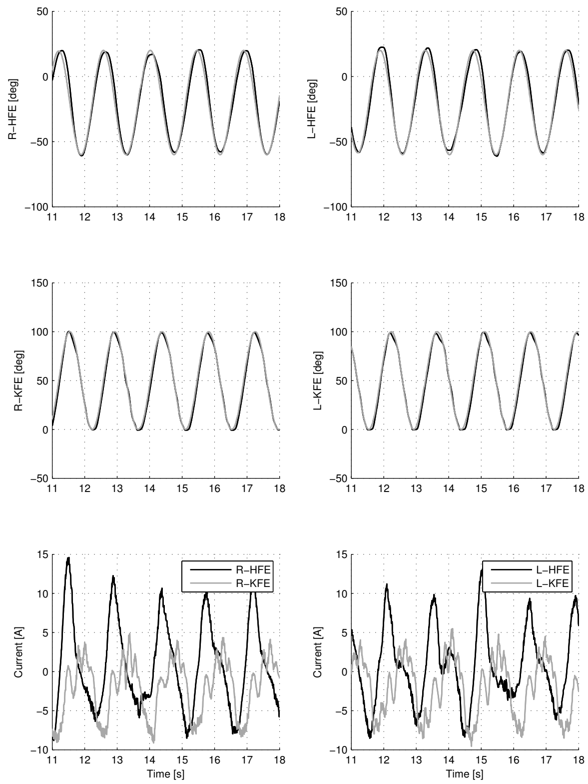

Fig. 9. Sinusoidal position tracking experiment using motors only

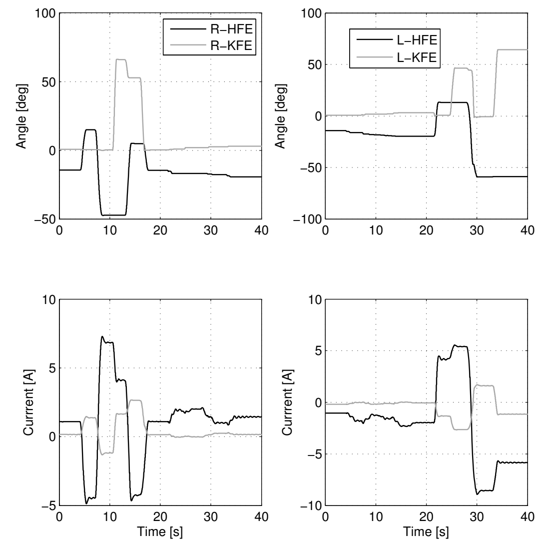

Fig. 10. Swing leg gravity compensation experiment using motors only

electromagnetic and pneumatic dynamics will be possible.

IV. Preliminary experiments

This section presents some preliminary experiments with the new robot.

A. Motor drive experiment

To check the performance of the electric drive, we did a leg swinging experiment using the HFE and KFE motors (PAMs were not used). First, we demonstrate an experimental result of simple sinusoidal swinging. All of the passive joints are locked rigidly by small clamps. Fig. 9 shows the timeline of the joint angle, torque and motor current. The swing period is 1.3 s, where 15 A (the maximum output current of the motor drivers) is required. This is not the limitation of the joint speed because we used here just a high-gain PD tracking. Even though the output current hits the maximum torque, we found no heating at the motors. Since the motion is relatively fast, torsional flexion appeared around CFRP pipe at the base, which leads forward/backward acceleration of the HFE pivot. This is why some aperiodic errors are seen in the motor current. Howerver, we expect this does not cause any problems in walking assist control because the robot is worn by human subjects.

Next, a simple G-comp test was carried out, where the operator change the robots posture by hand. The result is shown in Fig. 10. Smooth response to external force is achieved. The result demonstrates that sensorless torque control is possible for a swinging leg with electric motors, and that the selection of the motors is valid.

B. PAM drive experiment

To test the sensorless torque controllability of PAMs, a similar G-comp test was carried out. Again, all the passive joints are fixed rigidly. Since we are using pressure control valves, desired pressure must be computed to compensate the gravity. Therefore, force-contraction profile of PAMs are calibrated before the experiments. This is well fitted by a family of polynomial curves using least square. To enjoy the passive stability of antagonistic drive, small agonistic tension (50 N) is applied at HFE and AFE joints.

The experimental data is depicted in Fig. 11. In this experiment, contraction forces from PAMs are measured using the inline force sensors. One can see there some errors between the commanded torque and the generated torque computed from sensors. For example, from 40 s to 45 s, the left HFE joint torque is not consistent with the desired G-comp torque. During this time period, the human operator is partially supporting the thigh link by hand.This external force causes the error in the torque. This shows obvious result: zero torque error means zero external force.

Then, if a human subject wear the exoskeleton, can we identify the source of the external force? Namely, is it wearer? or other disturbance? Also, there can be clearly seen some delay even if there is no external force. This is due to the response of the pressure regulators and compressibility of the air. How to distinguish these three are left for future work.

V. Conclusion

This paper described our novel hybrid drive lower-extremity exoskeleton robot XoR2, an improved version of XoR. Its design concept, details of the new hardware, and basic experimental results were presented. The robot has a

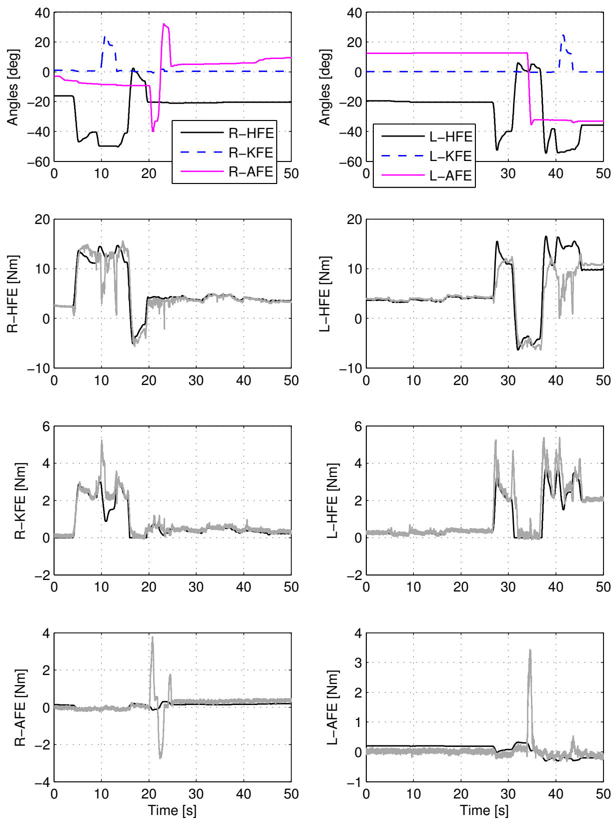

Fig. 11. Gravity compensation experiment using PAMs only

total of 14 joints, among which six flexion/extension joints are powered. Pneumatic artificial muscles were combined with small high-response servo motors for the hip and knee joints, and were arranged antagonistically at the hip and ankle joints to provide passive stability. The robot weight is 20 kg without valves and power sources, and the size is adjustable. The robot could swing its legs quickly using electric servomotors, and also compliantly interact with external forces using electric servomotors, or pneumatic artificial muscles by compensating the gravity. Inline miniture force sensors were fabricated to measure external force caused by either the wearer or other distubcance. The experimental results showed that the proposed mechanisms, sensors and control systems were effective, and hybrid drive is promising for a non-power-autonomous, but high-performance (torque-controllable, high-speed, backdrivable) mobile exoskeleton robot. It is very likely that we can easily reduce the weight to 15 kg, and the volume to the two-third, without sacrificing anything.

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