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A Lower Limb Exoskeleton Design for Assisting the Disabled

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Abstract:

This project investigates the drawbacks of present exoskeletons used for lower limb disabled people, focusing on the improvement of the design of an exoskeleton to reduce these disadvantages and make the exoskeleton more suitable to the disabled, these improvements are intended to increase the comfortability, flexibility and convenience of the exoskeleton.

Keywords: Lower limb exoskeleton, Assisted robot, Wearable robot, Mechanical design, Design simulation

1. Introduction

1.1 Background

According to United Nations statistics,Today, the world population is over 8 billion people and more than one billion people, or approximately 15 percent of the world's population,live with some form of disability[1] In another research, walking is the most common mode of transportation chosen by people with disabilities to spend their leisure time[2]. Therefore, it is necessary to provide walking ability support to a large number of disabled people as it is very important for them.

Table 1. The modal split for journeys to recreational and leisure venues

Modal split for journeys to recreational and leisure venues.

Main mode by distance travelled	Disabled persons (%) $N = 238$	Non-disabled persons (%) $N = 49$
Walk	25.21	8.16
Cycle	5.04	24.49
Driving a car	12.61	28.57
Passenger in a car	25.63	16.33
Tram	14.71	8.16
Bus	11.76	8.16
Taxi	3.36	2.04
Other (PKS coach)	1.68	4.08
Total	100.00	100.00

The exoskeleton has integrated advanced technologies from various robots. For example, using human-machine technology to detect muscle signals for control, using clinical gait analysis data to analyze the movement[3,4]. Consequently, the exoskeleton is a great tool for helping individuals with disabilities.

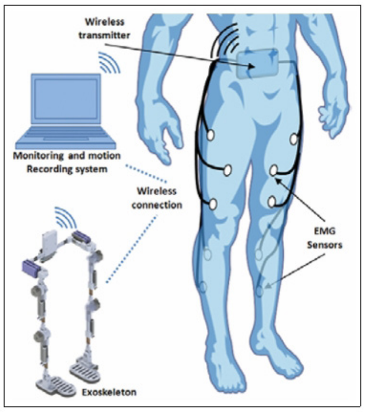

Figure 1. The muscle signal

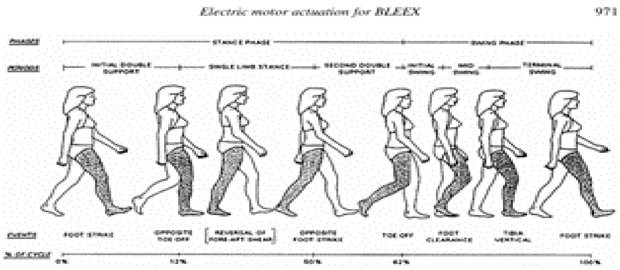

Figure 2. The gait Analysis

1.2 Motivation

The exoskeletons can be applied in various fields such as military, medical, industry and so on. The last column in Figure 3 shows the application areas of various exoskeletons[5,6].

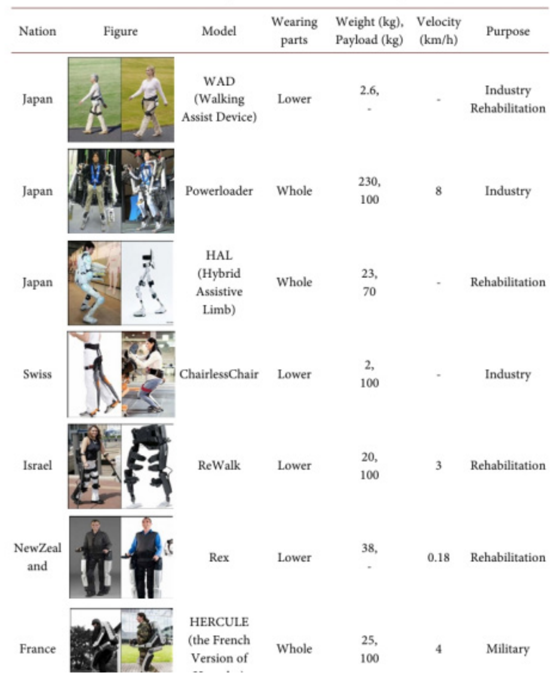

Table 2. Other countries—Summary of exoskeleton robot development [16]-[22].

Nation	Figure	Model	Wearing parts	Weight (kg), Payload (kg)	Velocity (km/h)	Purpose
Japan		WAD (Walking Assist Device)	Lower	2.6, -	-	Industry Rehabilitation
Japan		Powerloader	Whole	230, 100	8	Industry
Japan		HAL (Hybrid Assistive Limb)	Whole	23, 70	-	Rehabilitation
Swiss		ChairlessChair	Lower	2, 100	-	Industry
Israel		ReWalk	Lower	20, 100	3	Rehabilitation
NewZealand		Rex	Lower	38, -	0.18	Rehabilitation
France		HERCULE (the French Version of	Whole	25, 100	4	Military

Figure 3. Exoskeleton application field

The exoskeletons are majorly used in the military and medical area , while rarely used in civilia. Furthermore, medical exoskeletons are primarily utilized for rehabilitation rather than to aid in the living of disabled people. As a result, the goal of this research is to design an exoskeleton to support disabled people with lower limb difficulties in their daily life.

Current exoskeletons used for lower limb disabled people focus on the performance but neglects the user experience such as comfortability or convenience. For example, in Figure 4, the exoskeleton only has a rectangular chassis on the waist part which will cause discomfort when the user wears it [7]. Thus, the goal of this research is to improve the exoskeleton user experience.

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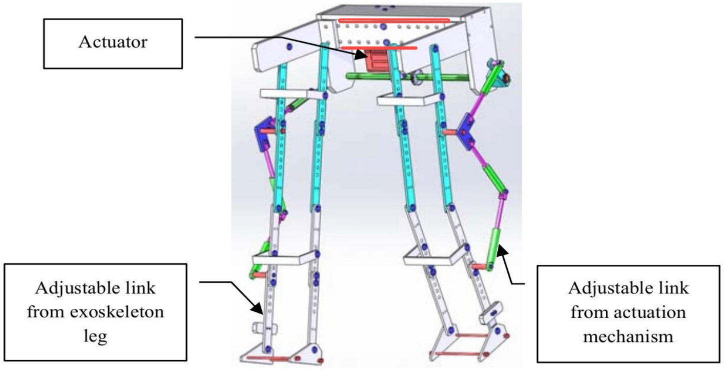

Figure 4. Waist design of other exoskeletons

2. Proposed Approach

2.1 Problem Statement

In the research of current exoskeletons, our team discovered that these exoskeletons have several disadvantages: Very heavy, expensive, low comfortability, and the design is complicated. These disadvantages strongly prevent disabled people from being able to afford such an exoskeleton.

Figure 5. Current exoskeleton

In order to reduce these drawbacks and lower the exoskeleton cost for the disabled, this project focuses on the improvements of the design of an exoskeleton, aiming to decrease its complexity, and increase its comfortability, flexibility and convenience.

2.2 Proposed Approach

The improvements of the designs are based on the prototype which is shown on Figure 6 .

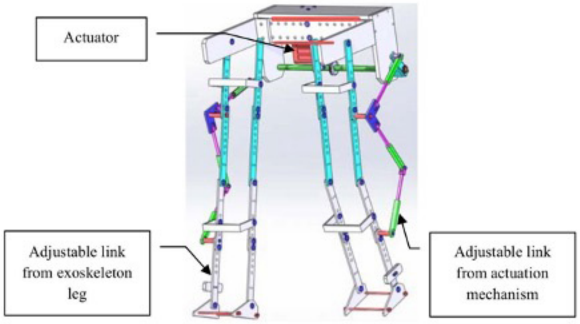

Figure 6. The prototype skeleton

2.2.1 Lumbar pad

A lumbar pad is added to the exoskeleton to increase comfortability. The physical quality Pressure is used to measure the comfortability.

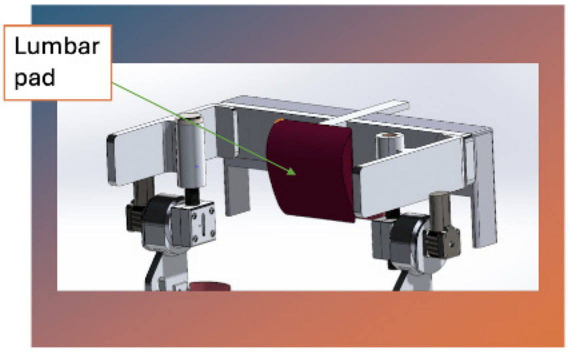

Figure 7. The exoskeleton with lumbar pad

In the prototype, the contact area between the exoskeleton and operator on the waist part is the red line (As shown on the graph), which is approximately:

$5mm \times 300mm^2 \times 2 = 3000mm^2$

The lumbar pad is designed to fit the waist curve of the human body, the area is about:

$20000mm^2$

which is almost 6 times larger than the previous one. As the pressure is calculated by: F¡Â$A = P$. Under the same force, the pressure on the lumbar pad will be much smaller than on the prototype waist part. Thus the operator will feel much more comfortable when wearing the improved exoskeleton.

2.2.2 Motors

To increase the flexibility of the exoskeleton, 4 motors are placed in joints as shown on Figure 8.

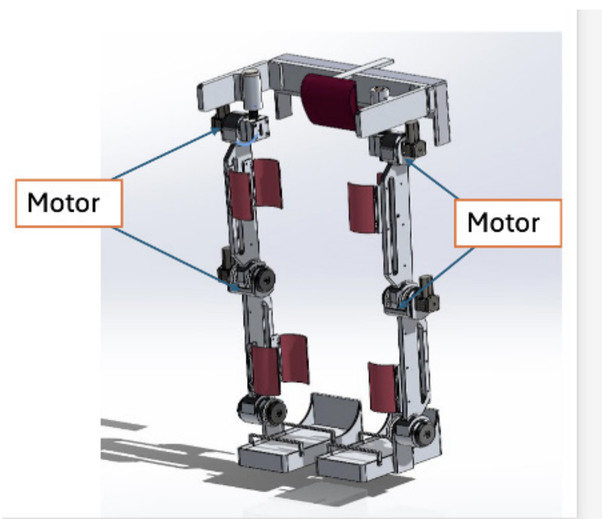

Figure 8. The designed exoskeleton with 4 motors

The motor is Vexta AHX5100KC, the specification of this motor is shown on Figure 9. There are several reasons for choosing this motor, firstly, this type of motor has sufficient power and torque to drive the exoskeleton, and secondly, the motor is relatively low weight. From the research of the current exoskeletons, another team also used this type of motor in their project [8], which verified that the motor is suitable for providing power to the exoskeleton.

TECHNICAL SPECIFICATIONS OF VEXTA AHX5100KC SERVOMOTOR

SERVO MOTOR	
Nominal Output Power (W)	100
Nominal Voltage (V)	24
Nominal Current (A)	6
Maximum Current (A)	9
Nominal Torque (Nm)	0,4
Maximum Torque (Nm)	0,5
Nominal Velocity (rpm)	2500
Maximum Velocity (rpm)	3190
Weight (kg)	1,4
GEAR	
Gear Ratio	100
Efficiency	0,85
Moment of Inertia (kgm^2)	$0,56.10^{-4}$
Weight (kg)	1,5

Figure 9. Technical Specifications of Vexta AHX5100KC motor

The prototype is powered by a single motor that is attached to two links; however, the flexibility of the exoskeleton will be limited by the design of the links, and the power that the motor produces is insufficient to drive the exoskeleton. In our design, each motor in four joints provides power to move legs, making the exoskeleton more flexible.

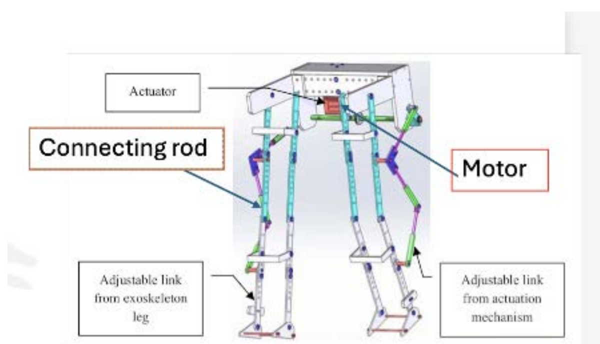

Figure 10. The power system of the prototype

2.2.3 Lumbar pad sensor

To increase the convenience and comfort of the exoskeleton, a force-sensitive resistor is used to adjust the position of the lumbar pad automatically. A rack and pinion driving system is used to transfer the circular motion into linear motion which drives the lumbar pad forward and backward. In this case, a motor is connected to the gear to provide power.

The whole process starts with the force-sensitive resistor (FSR) detecting the force applied to the user's back. If the force detected is above the maximum which is setted to be 9N, the motor will rotate anticlockwise to turn the gear and bring the pinion and lumbar pad away from the user's back until the exerted force is between 3N to 6N. It will perform the opposite process when the lumbar pad is not tight enough (e.g., the exerted force is below minimum

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which is 3N), in which the motor turns clockwise to move the lumbar pad forward. Eventually, the lumbar pad will remain at a position where the force exerted is between the maximum and minimum range (3N to 9N). Therefore, a suitable amount of force will be exerted by the lumbar pad on the user's back, thus ensuring the exoskeleton is in contact and is not too tight or loose. This can also be a user-set value based on their preference.

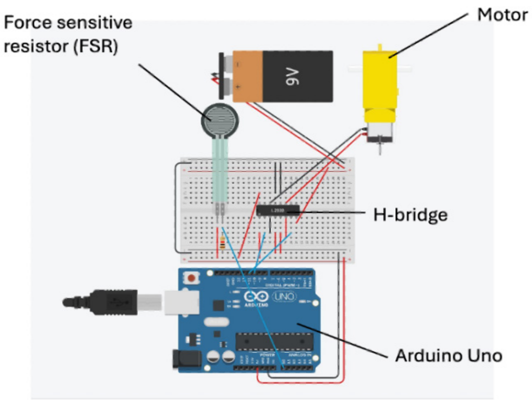


Figure 11. Model in tickercad.com

This automatic adjustable lumbar pad system is simulated and controlled in Arduino. As shown in Figure 11, the sensor and motor are both connected to an Arduino Uno board, as the FSR is connected to Pin A0 for input and Pin 10 and 11 for the motor for output.

```
int sensor = 0;
void setup () {
  pinMode(A0, INPUT);
  sensor pinMode (10, OUTPUT);
  servomotor pinMode(11, OUTPUT));
}
void loop() {
  int sensor = analogRead (A0) ;
  if (sensor >9) {
    digitalWrite (10,LOW) ;digitalWrite(11, HIGH);} //servo turns anticlockwise
  } else if (sensor < 3) {
    {digitalWrite(11,LOW) ;digitalWrite(10,HIGH) ;} //servo turns clockwise
  } else {
    digitalWrite (10,LOW) ;digitalWrite(11, LOW);
    break;} //stop
  }
}
```

Figure 12. The code

Integrating the same logic of the control into the code, shown in Figure 12, the sensor reads the analog value of the force, and the motor will turn clockwise or anticlockwise based on the statement algorithm. If the inputted value is between 3N to 9N, the motor will stop, and the loop will break, therefore maintaining the lumbar pad at a comfortable position.

3. Results and Discussions

3.1 Simulation of the Exoskeleton

The Video 1 shows the simulation of the improved exoskeleton by SOLIDWORKS MOTION ANALYSIS. This video illustrates that the design of the exoskeleton is successful, after installing 4 motors on the joints, the movement of the upper limb and lower limb is more fitted for human walking mechanisms.

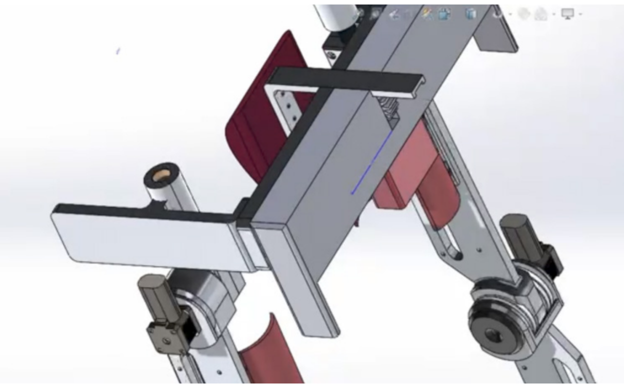
Video 1. Simulation of improved exoskeleton

Compared with the initial one, which has the same power system as the prototype, as shown on Video 2, the motor only provides power to move the upper limb, which is very stiff and inflexible. Consequently, the flexibility of our exoskeleton is increased by installing motors on joints.

Video 2. Simulation of initial exoskeleton

3.2 Lumbar pad

Video 3 shows the movement of the lumbar pad. The gear system is controlled by the force sensitive resistor sensor, which drives the lumbar pad to move forward and backward to adjust the position. From this video, the design of the mechanical moving system of the lumbar pad is verified to be feasible.



Video 3. The simulation of the motion of lumbar pad

3.2.1 The advantages of using lumbar pad

The lumbar pad brings several advantages to users, these advantages include:

● Improved Comfort: The lumbar pad is large and soft. When wearing the exoskeleton without the lumbar pad, the user will feel very uncomfortable. Thus the lumbar pad is important as it improves comfort.

● Prevent further injury: The lumbar pad spreads out the force more evenly to users' backs. Without the lumbar pad, users will experience severe waist pain when wearing the exoskeleton and eventually lead to waist injury.

3.3 Simulation for the Pressure Sensor(Matlab)

There are two force limits settled in the code of the pressure sensor which enable the lumbar pad to change its position under appropriate force. The simulation code is in Figure 13, and the simulation graph is in Figure 14.

In the graph, the blue line represents the scenario where the user is not lying on the pad, so its position remains unchanged. From 5 to 14 seconds, a user slowly leaned on the lumbar pad, the sensor kept detecting the force exerted on the lumbar pad, as shown on the green line. At 14 seconds, the sensor detected the force equal to (or greater than) 9N, then from 14 and 25 seconds, the pad gradually moved back until the force detected by the sensor was between 3N to 6N as represented by the red line. Finally, the pad stops moving, as indicated by the purple line, where the force remains constant.

```
t = linspace(0, 30, 1000);
pressure = zeros(size(t));

P_max = 9;  % uplimit force (N)
P_comfort_min = 3;  % comfort force low (N)
P_comfort_max = 6;  % comfort force up (N)
t_contact = 5;  % when user lean on the lumber (s)
t_exceed = 14;  % when detect the uplimit force (s)
t_retract_start = 14;  % time when lumber move back (s)
t_retract_end = 25;  % time when lumber move to the comfort level(s)

tau_increase = (t_exceed - t_contact) / 5;
tau_decrease = (t_retract_end - t_retract_start) / 5;
comfortable_value = P_comfort_min + (P_comfort_max - P_comfort_min) * rand;

for i = 1:length(t)
    if t(i) < t_contact
        pressure(i) = 0;
    elseif t(i) >= t_contact && t(i) <= t_exceed
        pressure(i) = P_max * (1 - exp(-(t(i) - t_contact) / tau_increase));
    elseif t(i) > t_exceed && t(i) <= t_retract_end
        pressure(i) = P_max - (P_max - comfortable_value) * (1 - exp(-(t(i) - t_retract_start) / tau_decrease));
    else
        pressure(i) = comfortable_value;
    end
end

figure;
hold on;

plot(t(t < t_contact), pressure(t < t_contact), 'b', 'LineWidth', 2);
plot(t(t >= t_contact & t <= t_exceed), pressure(t >= t_contact & t <= t_exceed), 'g', 'LineWidth', 2);
plot(t(t > t_exceed & t <= t_retract_end), pressure(t > t_exceed & t <= t_retract_end), 'r', 'LineWidth', 2);
plot(t(t > t_retract_end), pressure(t > t_retract_end), 'm', 'LineWidth', 2);

legend('no user lying on the lumber', 'when user begin lying on the lumber', 'when the lumber move back', 'when lumber reach the comfort level');
xlabel('time(s)');
ylabel('force(N)');
title('The Force Detecting of the Force Sensor of the Lumber');
grid on;
hold off;
```

Figure 13. Whole Simulation Code

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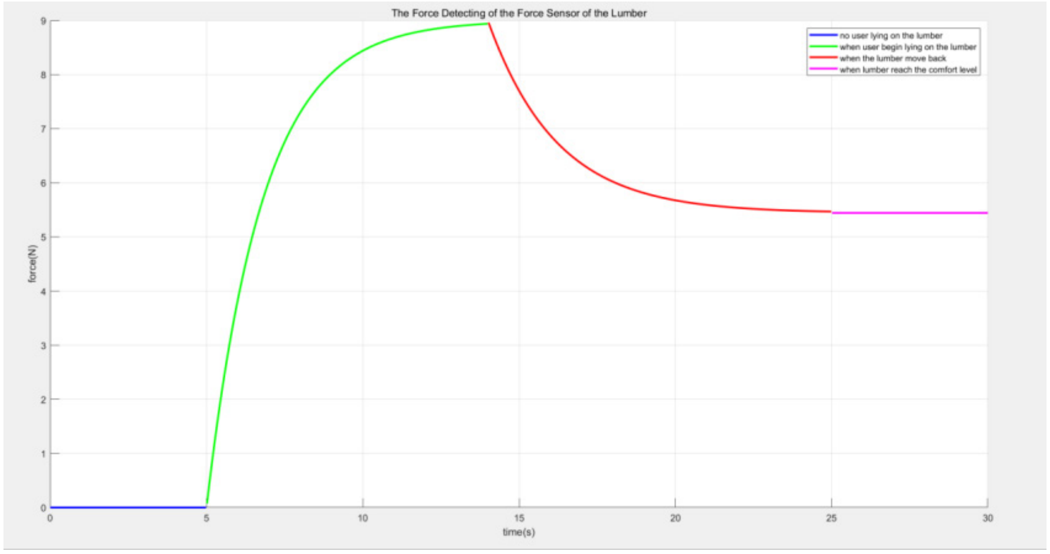

Figure 14. MATLAB Simulation Output Graph

3.3.1 The advantages of using the pressure sensor

The pressure sensor is placed under the lumbar pad that can control the movement of the lumbar pad. There are several advantages of using a pressure sensor:

● Intelligent: The pressure sensor monitors the contact force between the lumbar pad and user, which the lumbar pad will adjust its position automatically if the contact force is too high or too low. The function of the pressure sensor avoids manually changing the position of the lumbar pad, which is not only intelligent but also convenient.

● Increased performance: The function of the pressure sensor enhances the exoskeleton's compatibility with the user's body as it makes the lumbar pad fit the user better, which also increases stability between the exoskeleton and users.

● Comfortability: The lumbar pad, which is very soft and large, improved the exoskeleton's comfortability. The integration of the pressure sensor allows the lumbar pad to change its position to better fit the user, making the user feel more comfortable.This function also helps prevent waist pain and injury.

● Convenience: The integration of pressure sensor and lumbar pad also increases the convenience of the exoskeleton, since the function prevents the user manually changing the position of the lumbar pad.

4. Conclusion

From the proposed approach and results, the improvements of the design successfully increases the comfortability, flexibility and convenience of the exoskeleton, which make it more suitable for lower limb disabled people .

4.1 Contribution

● Relatively low cost: Our exoskeleton not only uses relatively cheap material, but also follows a lightweight design, thus the overall cost decreased without compromising the exoskelton's functionality. This makes our exoskeleton more affordable for individuals who cannot afford expensive options on the market, thereby improving their quality of life to a certain extent.

4.2 Limitation

Due to the limited duration of the research and the fact that our team members are distributed globally without access to specialized laboratories, several limitations are present in the research:

● Lack of User Data: Throughout the design phase, the data used for our exoskeleton was from online resources rather than from actual users. As a result, some design parameters such as the size of the exoskeleton and the length of the exoskeleton legs, may not fully align with optimal ergonomic standards.

● Absence of Practical Experiments: Our team only designed the exoskeleton but did not manufacture a real one. There may be some defects in the structure of the exoskeleton or the algorithm of the pressure sensor. For example, the setted maximum and minimum contact force in the pressure sensor system does not account for various user factors such as weight, height, waist circumference, or skeletal structure, which means the setted force may change for different users. As a result, while the exoskeleton is theoretically feasible, it may not be practical in the real world.

5. Future Work

To further improve and produce a quality product, further investigation into the kinesiology of the human body is needed to optimize joint design, control systems, and dynamics of the exoskeleton. It will also be beneficial to embed intension perception using behavioral sensors such as inertial measurement units (IMU), to improve and perfect the control system of the exoskeleton. Lightening the weight and lowering the cost can also provide a better user experience and help more consumers access the product.

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Jinda Wan, Rongchi Gao, Mengdi Yuan, and Runze Xiang contributed equally to this work and should be considered co-first authors.

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