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# An untethered cable-driven ankle exoskeleton with plantarflexion-dorsiflexion bidirectional movement assistance



**Key words:** Ankle exoskeleton; Plantarflexion-dorsiflexion bidirectional assistance; Biological gait torque; Cable-driven; Gait detection

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# Motivation

- The joint-actuator based designs, whose actuator, power supply unit, and control unit are directly connected with the wearer's legs, often make the device too bulky, heavy. The rotational inertia applied to the wearer is large because of the extra mass.
- To reduce the extra weight, two methods have been proposed for exoskeletons, i.e., to reduce mass using a passive device and to allocate the main mass remotely and off-board using tethered techniques. However, the passive devices do not have high power output, and the tethered devices are not portable.
- To combine the advantages of being lightweight, having high power output, and portability, and to reduce the redundant rotational inertia applied to the wearer's leg, cable-driven ankle exoskeletons are proposed. However, most current cable-driven ankle exoskeletons achieve only plantarflexion movement.
- Moreover, some cable-driven exoskeletons apply two actuators to realize bidirectional assistance. Can it be achieved using only one actuator?

# Main idea

- In this paper we present an untethered cable-driven ankle exoskeleton that can achieve plantarflexion-dorsiflexion bidirectional motion using a pair of single motors for both legs.

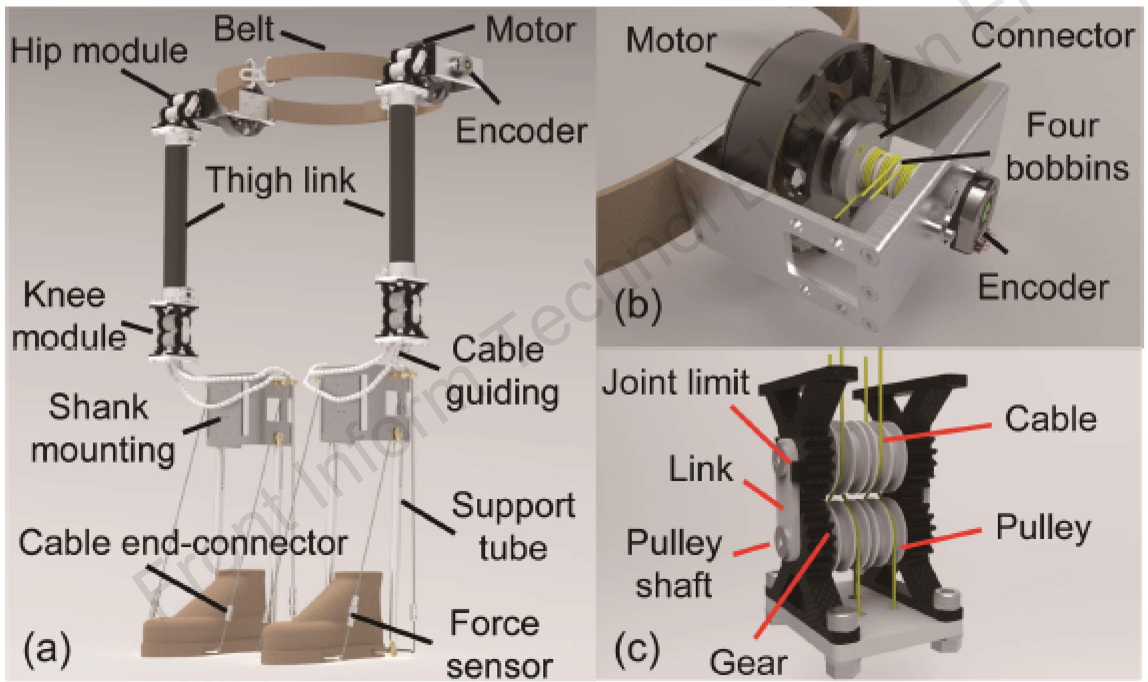


**Fig. 1 Overview of our untethered cable-driven ankle exoskeleton (a), overview of the power output module (b), and a detailed diagram of the knee module of the cable transmission system (c)**

# Method-Mechanical design

- Force and movement analysis of the end-effector is performed to assist the bidirectional movement of the ankle.
- Pulley assembly applied on the hip and knee modules is designed to keep the cable length unchanged, which can potentially improve the transmission efficiency.



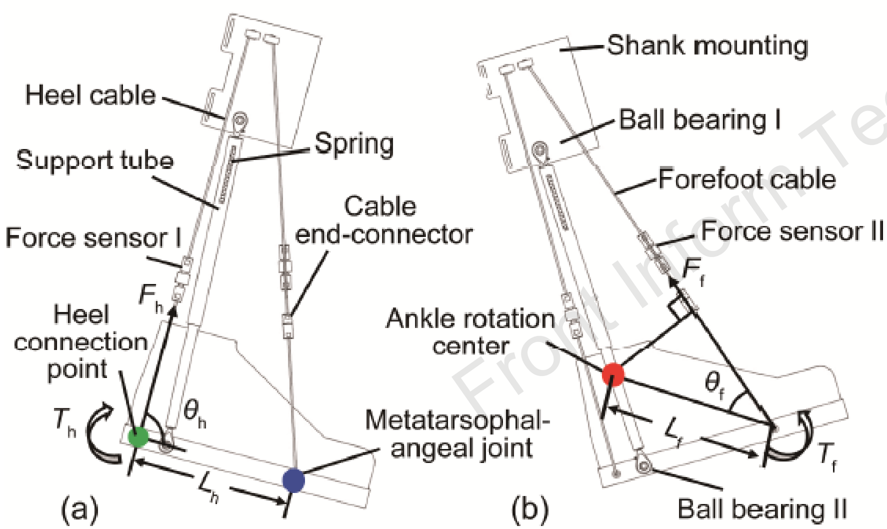


**Fig. 2 Force and movement analysis of the ankle motion in the sagittal plane with the exoskeleton on: (a) plantar-flexion; (b) dorsiflexion**

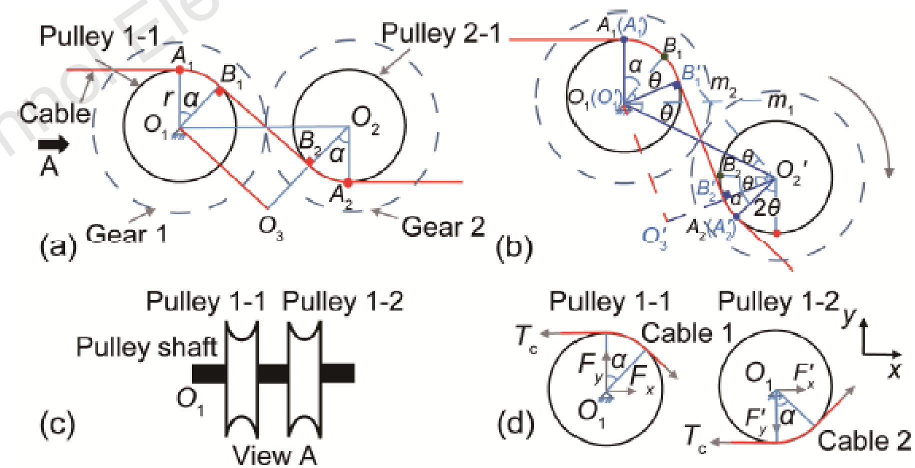


**Fig. 4 A section view of the pulley assembly, composed of four pulleys (pulleys 1-1, 1-2, 2-1, 2-2) and two gears (gears 1, 2) (a), kinematic analysis after gear 2 is rotated around gear 1 with an angle $\theta$ clockwise (b), partial view from view A (c), and the force analysis of pulleys 1-1 and 1-2 (d)**

# Method-Mechanical design (Cont'd)

- A cable length self-tensioning in the power output module is designed to compensate for the cable length difference of forefoot cable and heel cable.

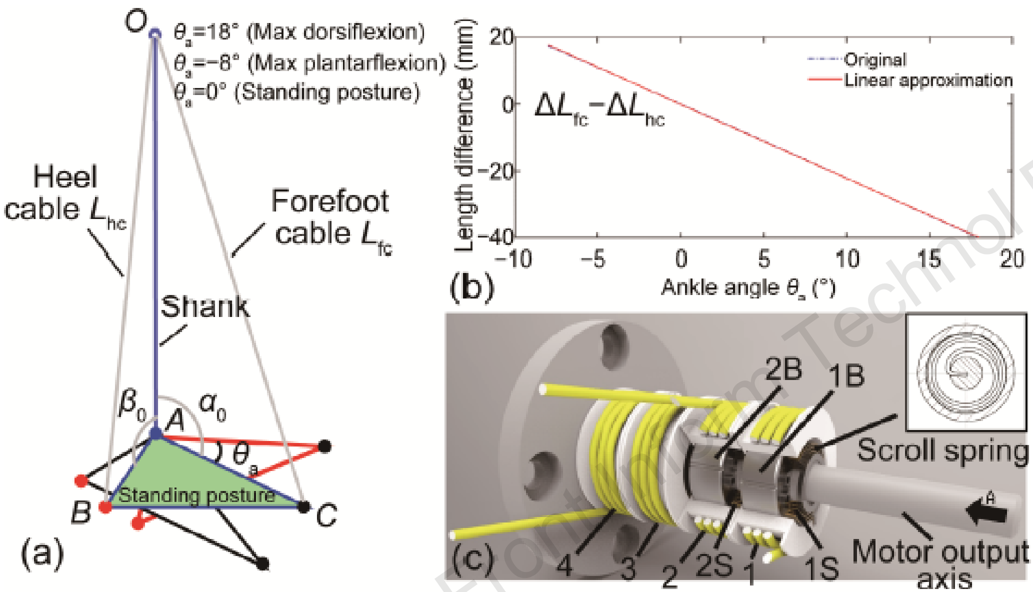


**Fig. 5 A diagram showing the foot under three states (a), the length difference between the two cables calculated from the basic parameters ($\overline{OA}$ =340 mm, $\overline{AB}$ =90 mm, $\overline{AC}$ =150 mm, $\alpha_0$=120°, $\beta_0$=160°) (b), and a cable length self-tensioning device diagram (c)**

**Fig. 11 An overview of the exoskeleton worn on the human body**

# Method-Gait cycle detection

- The human gait cycle can be divided into heel strike (HS), foot flat (FF), push off (PO), toe off (TO), and mid swing (MS).
- The gait states can be detected by the foot pressure sensor and the inertial measurement unit (IMU).

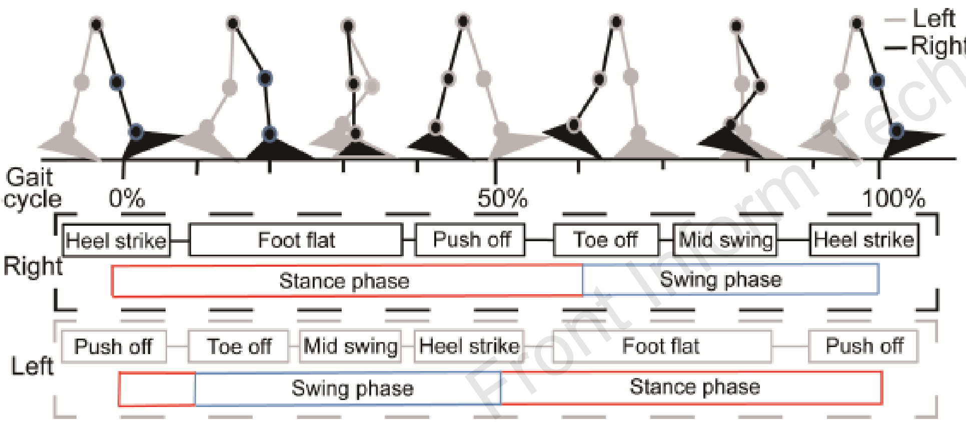


Fig. 6 State definition of a human gait cycle

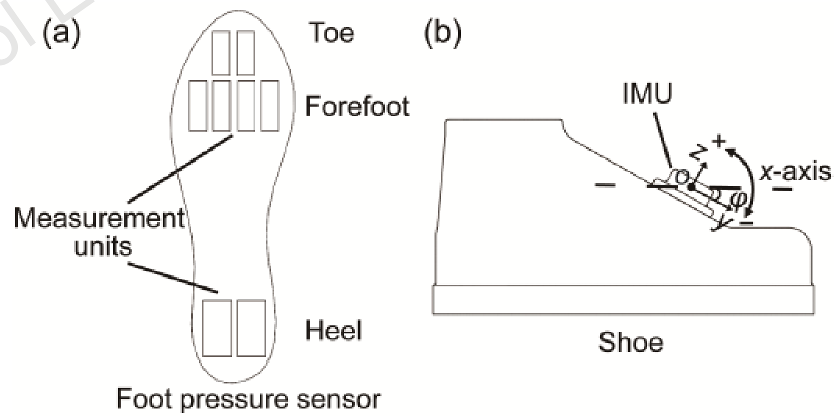


Fig. 7 Measurement units of the toe, forefoot, and heel of the foot pressure sensor (a) and placement of the IMU (b)

# Method-Controller design

- The gait detector is composed of the foot pressure sensor and IMU. It can detect the human walking and identify the gait cycle. Then the controller controls the execution unit to output the desired torque to the body by the feedforward and proportional-derivative (PD) controllers according to the gait cycle.

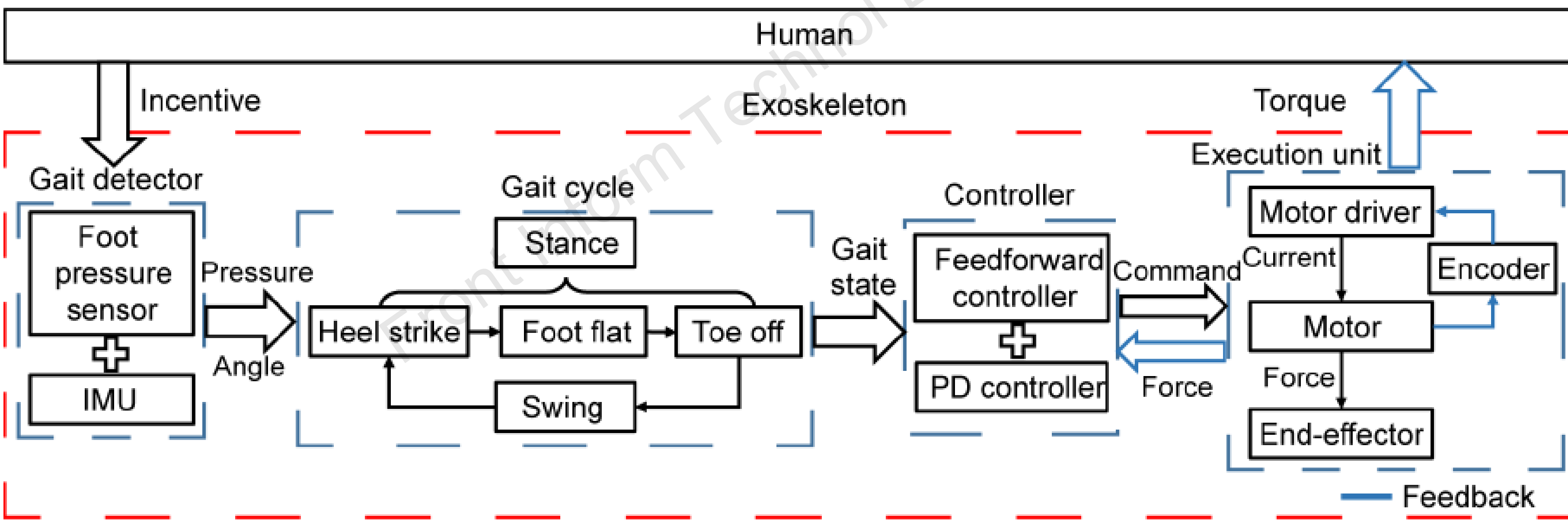


Fig. 9 Schematic of the exoskeleton architecture

# Results-Gait cycle detection

- ☐ Using the threshold method to individually complete gait cycle detection based on the data from the foot pressure sensor and IMU.
- ☐ Using the fusion strategy to identify the gait state during walking.

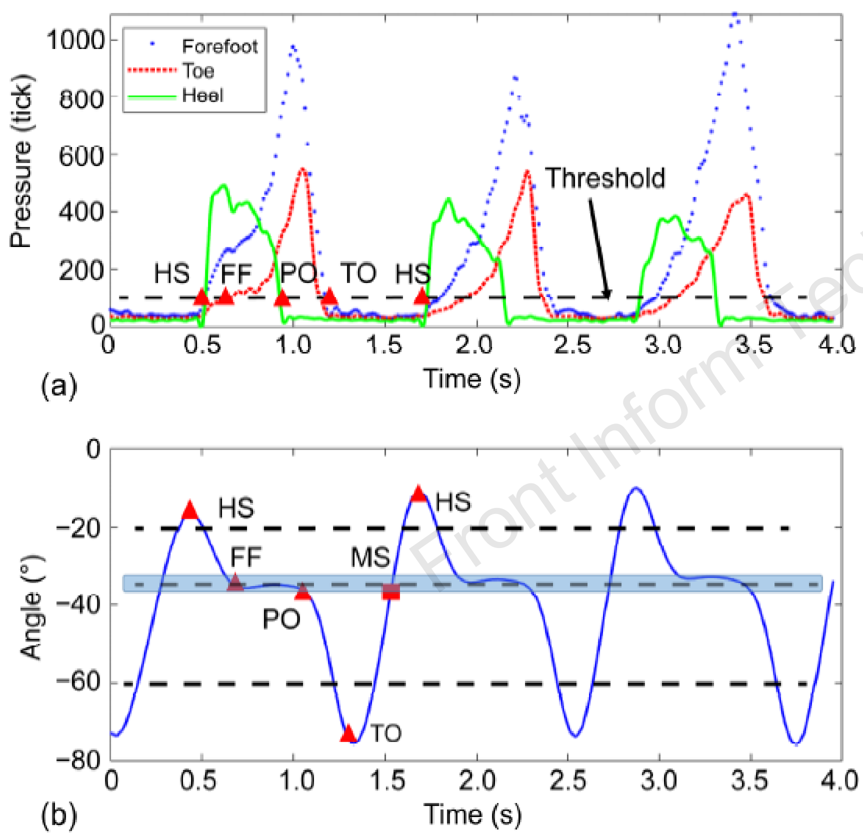


**Fig. 12 Gait states identified based on data from the foot pressure sensor and the IMU**

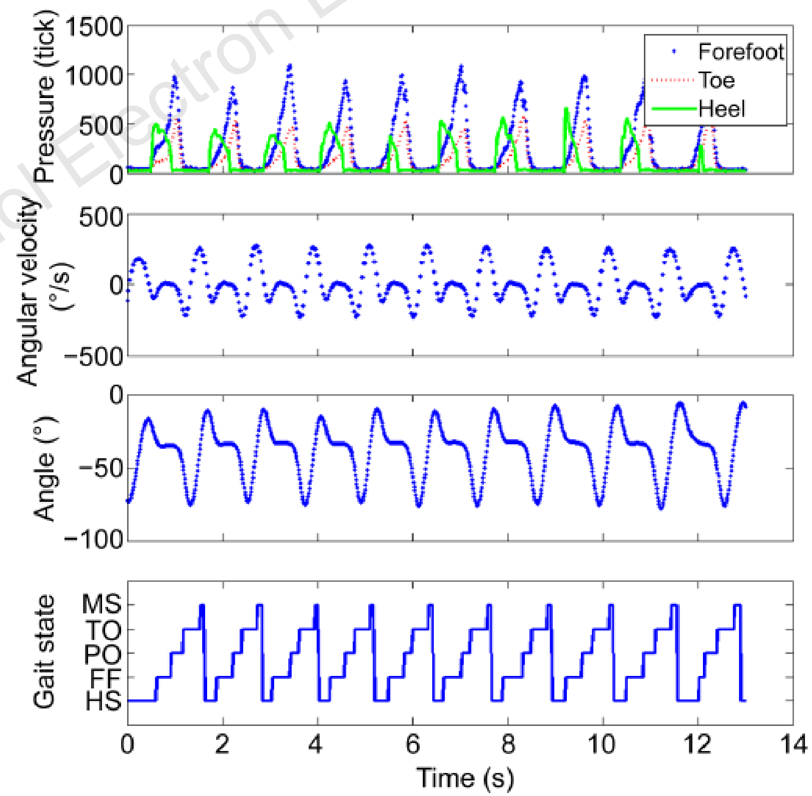


**Fig. 13 Gait state detection results distinguished by foot pressure, IMU angle, and angular velocity when the subject walked at a speed of 3 km/h with the exoskeleton on**

# Results-Biological gait torque tracking

- To validate the power output performance of the exoskeleton, an experiment tracking the desired biological torque was implemented.

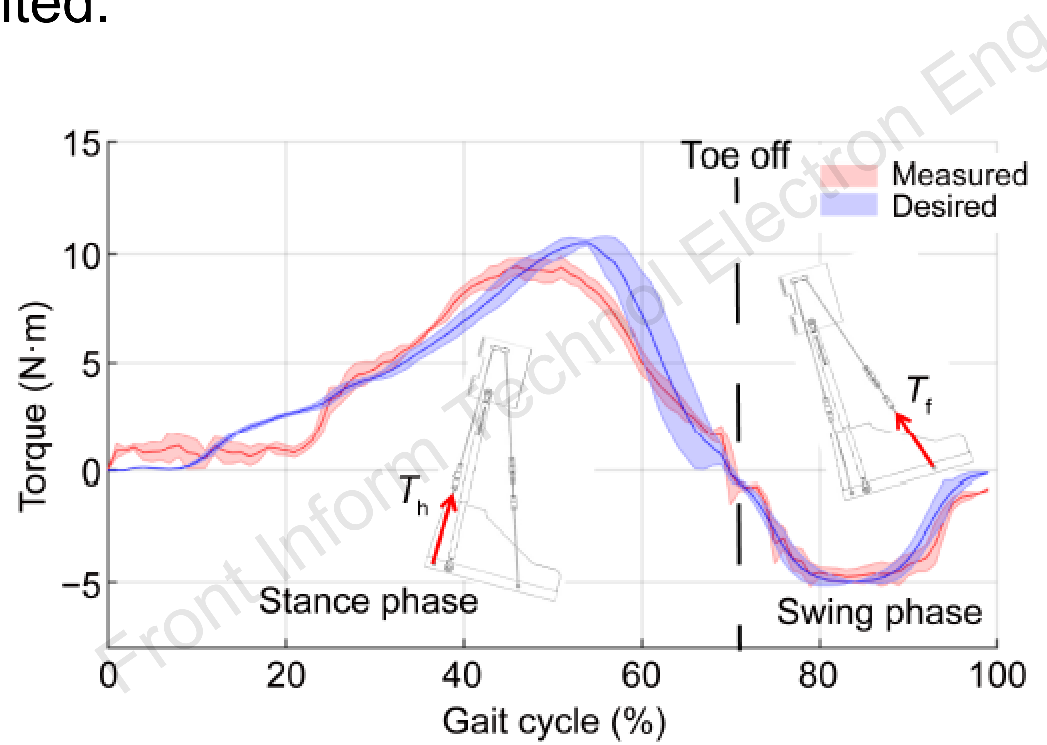


**Fig. 15 Stance phase and swing phase assistance torque provided by the exoskeleton compared with the desired torque**

# Results-Assistance effect evaluation by muscle activity

- The soleus activity was measured under three different conditions (No Exo, Power Off, and Power On). When the subject wore the exoskeleton with power on, the soleus activity was reduced by 5.2% compared to the without-wearing exoskeleton state, and 16.7% of energy was saved compared to wearing exoskeleton with power off.

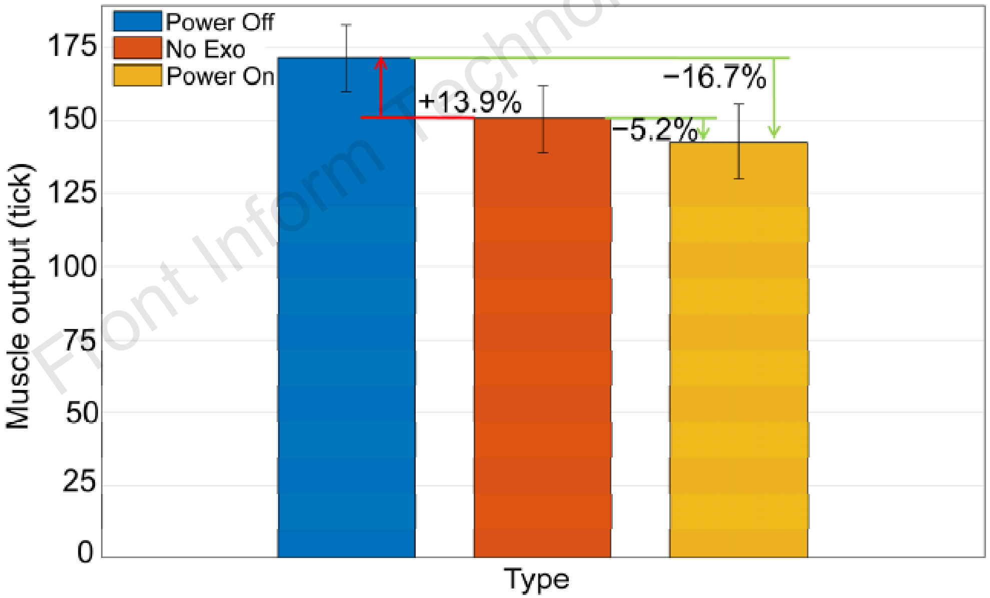


**Fig. 17 Short-term effect of exoskeleton assistance on the subject soleus's activity evaluated by the RMS EMG**

# Conclusions

The results indicated that for the subject walking on the flat ground, the untethered cable-driven ankle exoskeleton has the following advantages:

- The extra weight added to the wearer's legs is less and there is not much extra burden on the user
- The gait detection system can identify human gait states accurately and efficiently
- Plantarflexion-dorsiflexion bidirectional movement assistance can be provided by the exoskeleton
- The assistance torque provided by the exoskeleton can well track the desired ankle torque
- With the subject wearing the exoskeleton with the power on, the soleus muscle activity can be reduced by 5.2% compared with the without-wearing the exoskeleton state, which can potentially help the wearers reduce energy consumption

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