A method to calculate assistance force and torque when walking with a passive orthosis

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Summary

A mathematical method is described here for the calculation of the knee and ankle moments, and assistance torque in the sagittal plane during stane phase of walking with a passive ankle foot orthosis.

Introduction

We recently produced an Intrepid Dynamic Exoskeletal Orthosis (IDEO) prototype (figure 1[a]) by using digital scanning and modeling to improve fabrication efficiency. IDEO was originally developed at Walter Reed National Military Medical Center to improve gait, stability and function [1]. The device includes a knee cuff and a ankle foot orthosis insole, connected by a carbon fiber energy storing strut. Given that stiffness of strut is nonlinear and that the dynamic loading on the strut is complex, we would like to assess assistance force/torque provided by IDEO during locomotion by using the inverse dynamics (ID) approach [2].

Methods

The goal of our method is to 1) find the joint reaction forces and moments at ankle F'_{ax}, F'_{ay}, M'_a, and knee F'_{kx}, F'_{ky}, M'_k. Here we assume that shank length L_s, COM_s, r_s related to shank's center of mass (COM), the end position of strut P_1 and P_2 and strut length L_I and its COM location r_I, have been obtained through motion analysis, and that the masses of shank, foot and IDEO are given, and that the acceleration of foot is zero during stance phase. 2) find the forces and moments at two ends of the IDEO strut (figure 1[b]). F_{1x}, F_{1y}, M_1 and F_{2x}, F_{2y}, M_2. With the following equations, we can solve for the assistance torque/force provided at each connection point between orthosis and human body. Based on figure 1[c], we have derived the governing equations of the IDEO-Shank-Foot (ISF) as one segment.

$$\sum F_x = F'_{gx} - F'_{kx} = m_{ISF}\ddot{x}_{ISF} \tag{1}$$

$$\sum F_y = F'_{gy} - F'_{ky} - m_{ISF}g = m_{ISF}\ddot{y}_{ISF} \tag{2}$$

$$\begin{aligned}\sum M_{ISF} &= M'_{GRF} - M'_k + F'_{gx}\cdot h' + F'_{gy}\cdot a' \\ &+ F'_{kx}\cdot(L_s - r'_s)\cdot\sin\theta_s \\ &- F'_{ky}\cdot(L_s - r'_s)\cdot\cos\theta_s = I_{ISF}\ddot{\theta}_s\end{aligned} \tag{3}$$

Based on figure 1(d), we have derived the governing equations of the strut.

$$\sum F_x = F_{1x} - F_{2x} = m_I\ddot{x}_I \tag{4}$$

$$\sum F_y = F_{1y} - F_{2y} - m_I g = m_I\ddot{y}_I \tag{5}$$

$$\begin{aligned}\sum M_I &= F_{1x}\cdot r_I\cdot\sin\theta_s - F_{1y}\cdot r_I\cdot\cos\theta_s \\ &+ F_{2x}\cdot(L_I - r_I)\cdot\sin\theta_s - F_{2y}\cdot(L_I - r_I)\cdot\cos\theta_s \\ &+ M_1 - M_2 = I_I\ddot{\theta}_I\end{aligned} \tag{6}$$

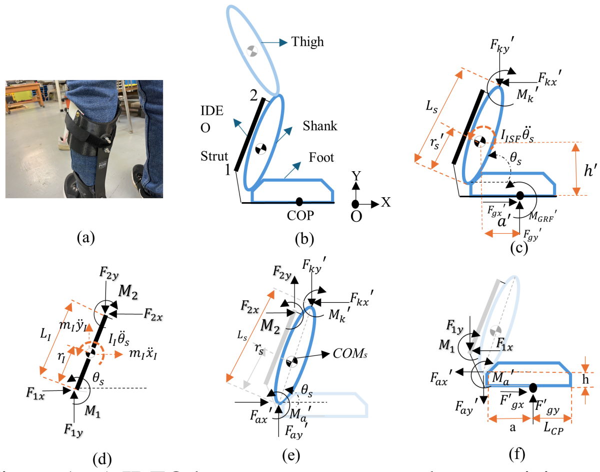

Figure 1: a) IDEO brace prototype wore by a participant; b) Lower body and IDEO strut representation for ID analysis c) Free body diagram (FBD) on ISF; d) FBD on IDEO strut; e) FBD on shank; f) FBD on ankle

Based on figure 1(e), we have derived the governing equations of the shank.

$$\sum F_x = F'_{ax} + F_{2x} - F'_{kx} = m_s\ddot{x}_s \tag{7}$$

$$\sum F_y = F'_{ay} + F'_{2y} - F'_{ky} - m_s g = m_s\ddot{y}_s \tag{8}$$

$$\begin{aligned}\sum M_s &= F'_{ax}\cdot r_s\cdot\sin\theta_s - F'_{ay}\cdot r_s\cdot\cos\theta_s \\ &+ F'_{kx}\cdot(L_s - r_s)\cdot\sin\theta_s - F'_{ky}\cdot(L_s - r_s)\cdot\cos\theta_s \\ &- F_{2x}|P_{2y} - COM_{sy}| - F_{2y}|P_{2x} - COM_{sx}| \\ &+ M'_a + M_2 - M'_k = I_s\ddot{\theta}_s\end{aligned} \tag{9}$$

Based on figure 1(f), we have derived the governing equations of the ankle.

$$\sum F_x = F'_{gx} - F'_{ax} - F_{1x} = 0 \tag{10}$$

$$\sum F_y = F'_{gy} - F'_{ay} - F_{1y} = 0 \tag{11}$$

$$\begin{aligned}\sum M_a &= F'_{gx}\cdot h + F'_{ay}\cdot a + F_{1x}\cdot|P_{1y} - a_y| \\ &+ F_{1y}\cdot|P_{2x} - a_x| - M_1 - M'_a = 0\end{aligned} \tag{12}$$

Discussion

In the future, we would like to conduct a validation study by measuring the assistance torque/force via torque sensors.

Conclusions

We have developed a method that aims to accurately calculate the assistance torque/force during locomotion.

References

[1] Hoyt BW et al. (2021). *Injury*, **52**: 3505–3510.
[2] Uchida TK and Delp SL. (2021). *Biomechancis of Movement*; MIT Press