Kinematic and Force Analysis of Hip – Exoskeleton Interaction

Sean Oviedo

11/29/2019

ME 476C - 005

Biomechatronic Hip Exoskeleton Team (BHET) – B9

1 Background

The Northern Arizona Biomechatronics Lab is focused on improving mobility for individuals with diminished neuromuscular functions. This is through design and development of robotic prosthetic devices that provide assistive torque to the wearer during the walking cycle. The NAU Biomechatronics Lab uses these devices to measure walking characteristics and to develop the way assistance is applied.

The purpose of the project is to develop an exoskeleton for assisting the hip joint during walking. The Biomechatronic Hip Exoskeleton (BHE) project will complement the work already done by the NAU Biomech lab. The hip joint has three degrees of freedom about which in can freely rotate: Extension/flexion, Abduction/adduction, and internal/external rotation. The BHE will aid the hip joint during extension/flexion.

The BHE team has proposed a design that utilizes flexible chords to apply the assistive torque to the hip (Figure 1.1). Each of the wearer's legs will have two cords, one in front and one in the rear, allowing for force to be applied as the hip moves in extension or flexion.

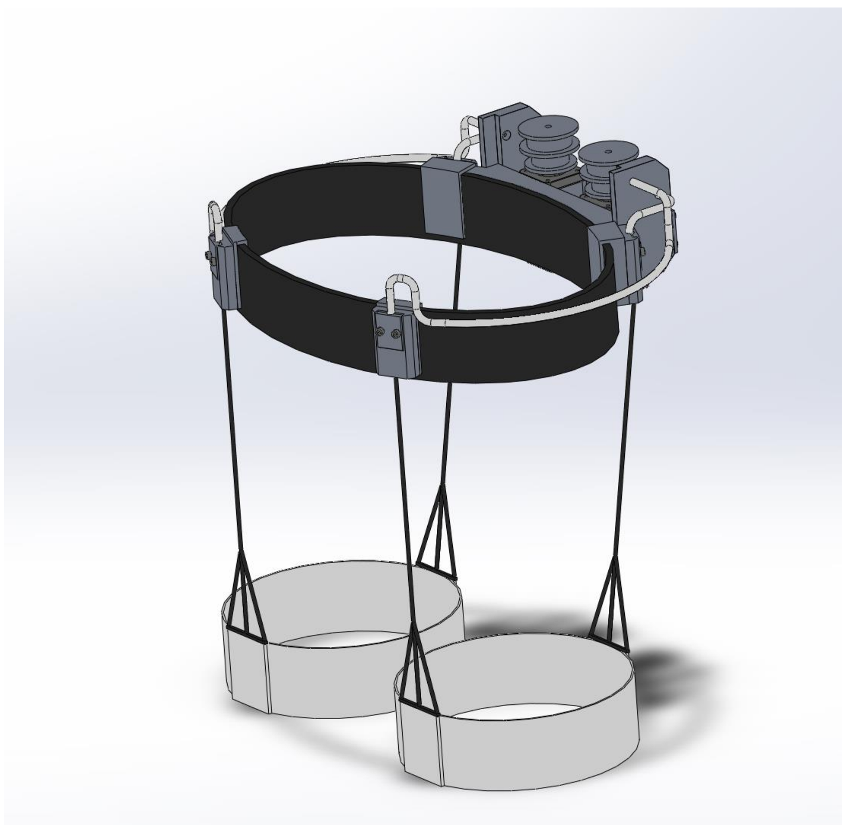

Figure 1.1 Current BHE design

2 Introduction

The purpose of this report is to analyze the kinematic relationship between the hip joint and the pulleys. Developing a kinematic model for the system is critical to understanding the maximum force that the BHE needs to apply and will allow the team to optimize dimensional relationships in the frame and drivetrain of the device.

The actuation system chosen for the BHE design utilizes cords to apply force to the wearer. This method was chosen because it allows the wearer to maintain full range of motion along the non-assisted DOF of the hip. This also offers more freedom for the motor and drivetrain configuration, since the cords can be routed through complex bends to the desired position.

The use of fabrics in exoskeletons has been explored at the Harvard Biodesign Lab, which developed a hip exoskeleton that utilized webbing material to provided assistive torque to the wearer. The webbing material is paid out and taken up by spools located on the back of the wearer, which means actuation only occurs during extension [1].

The customer needs for this project state that the torque assistance will be 30% of the wearer's natural hip joint torque during walking cycle. The device must further be able to deliver assistive torque throughout the entire ROM of the hip (during walking cycle). Research on the topic has shown that natural torque output as a function of body mass can peak at 0.75 – 1.0 $\frac{Nm}{kg}$ and angular displacement rang of ~45° ($\theta = 35°$ flexion, -10° extension) [1, 2]. The maximum moment applied to the hip is given by:

$$M_h = 0.30 T_n m_m \tag{2.1}$$

Where M_h is the torque applied by the BHE to the hip joint, T_n is the peak natural torque per unit body mass, and m_m is the maximum expected body mass.

Based on the literature and the peak mass of patients treated at the NAU Biomechatronics Lab (m = 60kg), the maximum torque the BHE needs to apply is $M_h = 18Nm$.

3 Kinematic Analysis

The peak force capability of the BHE is dependent on the geometric relationships between the actuation cord and the hip joint. The purpose of this analysis is to develop a series of equations that relates changing geometry of the design with known parameters (θ, M_h, and static dimensions). The resulting equations will be used to develop a MATLAB program that can analyze the effect of altering the actuation distance, a_i and motor torque capability. This is done by establishing a reference frame around the hips, with the y-axis aligned to the torso such that the relative motion of the legs is apparent. The following section will discuss the assumptions, variables, equations and results of the analysis.

3.1 Assumptions

- The hip joint is coplanar with both ends of the cords
- The structural elements of the BHE are rigidly attached to wearer reference such that their position relative to the hip joint is fixed
- Compliance of the cord material and soft tissue is ignored

- Force is applied to the wearer at the intersection of the force vectors (along lc_1 & l_{c2})

3.2 Variable Definitions

Figure 3.1 shows a diagram that illustrates the kinematic relationships of the system. Note that F_1 is present for illustrative purposes, for this depiction only F_2 would be acting on the system.

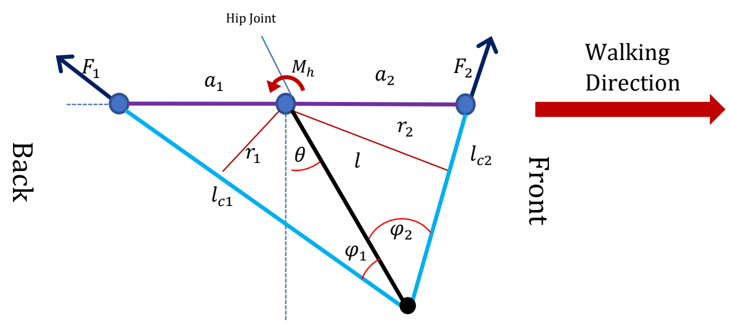

Figure 3.1 Kinematic diagram of hip and BHE interaction

Symbolic variables and descriptions used in the analysis are described in Table 3.1.

Table 3.1 Variable definitions and symbolic representations

Symbol	Description
$\boldsymbol{x_h}$	x-position of points connecting the cord to the leg
$\boldsymbol{l}$	Distance along the leg between the hip joint and intersection of the force vector
$\boldsymbol{l_c^*}$	Length of cord, measured as a straight line from actuation point to end of l
$\boldsymbol{M_h}$	Max specified torque applied to the hip by the BHE
$\boldsymbol{F^*}$	Magnitude of force applied along l_c
$\boldsymbol{a^*}$	x-distance between cord payout and hip joint
$\boldsymbol{\theta}$	Angle between l and the y-axis with $\theta = 0$ relating to a standing position
$\boldsymbol{\varphi^*}$	Angle between l and l_c
$\boldsymbol{r^*}$	Moment arm between l_c and hip joint

*Parameters specific to rear or front actuation points, denoted in calculations as subscripts 1 and 2 respectively.

3.3 Resulting equations

Based on the above diagram, the following relationships were derived:

$$l_{c1} = \sqrt{a_1^2 + l^2 - 2a_1 l \cos\theta} \tag{3.1}$$

$$l_{c2} = \sqrt{a_2^2 + l^2 + 2a_2 l \cos\theta} \tag{3.2}$$

$$\varphi_i = \cos^{-1}\left(\frac{l^2+l_{ci}^2-a_i^2}{2l_{ci}l}\right) \tag{3.3}$$

$$F_i = \frac{M_h}{l\sin\varphi_i} \tag{3.4}$$

Equations 3.1 & 3.2 express lc 1 and 2 in terms of θ. This is needed to relate the fixed dimensions (l, a_i) to φ_i. With the dimensional relationships established, the peak force can be calculated using equation 3.4. Full derivations of equations 3.1 – 3.4 can be found in appendix 4.1.

3.4 MATLAB Program

A script was created in MATLAB that applies the above equations. The purpose of this program is to identify the peak force required by the actuation cords and examine how that requirement changes with the point from which the cord is paid out, relative to the hips.

The program accepts proposed dimensions for a_1 & a_2 as an array and uses equations 3.1 – 3.4 to compute the peak force needed from the cord along the expected range of θ. Equation 2.1 is also used with the peak expected values of T_n & m_m to facilitate testing different parameters, if desired. Radius measurements for the pulley and motor input torque are input for rough calculations of the gear reduction required to achieve peak force.

The inputs for the program are summarized in __

- Length l
- Distances a_l & a_u
- Number of values between a_l & a_u, n
- Motor input torque, M_Torque
- Drive puller radius, r_pulley1 & r_pulley2

The script was run with values of a ranging from a_l=0.2m to a_u=0.4m, & n=3. The results are plotted in Figure 3.2 & Figure 3.3. The full MATLAB script can be found in appendix 4.2.

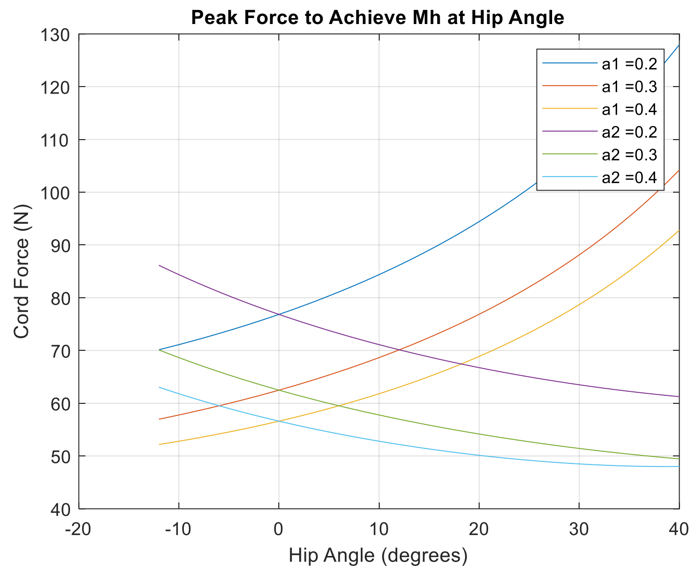

Figure 3.2 Peak force required for different values of a, through the extension/flexion range

The calculations demonstrate that cord force decreases as *a* increases, and that *a1* is should be longer to decrease required force. *a2* generally requires less force.

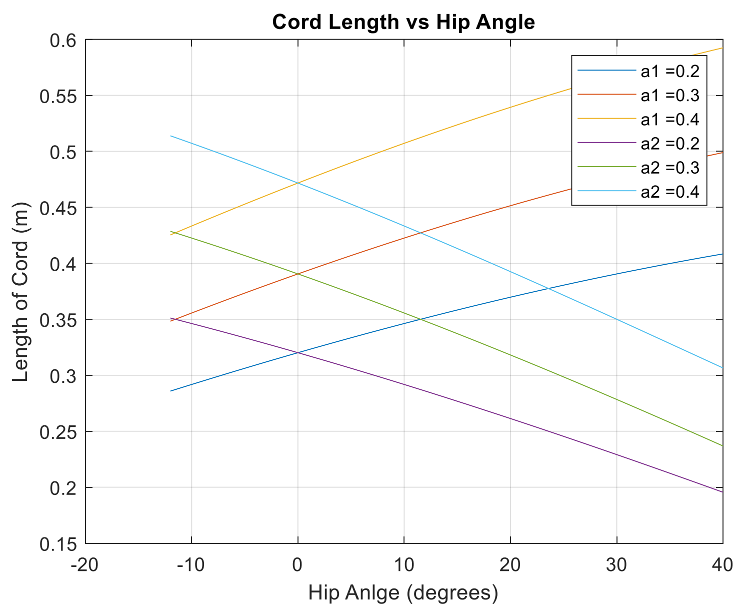

Figure 3.3 Length of front and rear cords through extension flexion range

Figure 3.3 shows the cord lengths through the ROM of the hip. This information will be used in further calculations to determine the front to rear cord payout/retraction ratio.

4 Conclusion

The results if the analysis has provided the BHE team with the fundamental equations that relate the geometry of the design and the force required. This has revealed the effect of changing the distances between the hip joint and actuation points on the BHE and the MATLAB code allows the team to model changes to optimize the design.

5 References

[1] A. T. Asbeck, K. Schmidt and C. J. Walsh, "Soft exosuit for hip assitance," *Robotics and Autonomous Systems,* vol. 73, pp. 102-110, 2015.

[2] Z. Shen, G. Allison and L. Cui, "An Integrated Type and Dimensional Synthesis Method to Design One Degree-of-Freedom Planar Linkages With Only Revolute Joints for Exoskeletons," *Journal of Mechanical Design,* vol. 140, no. 9, pp. 1-12, 2018.

6 Appendix

6.1 Equation Derivations

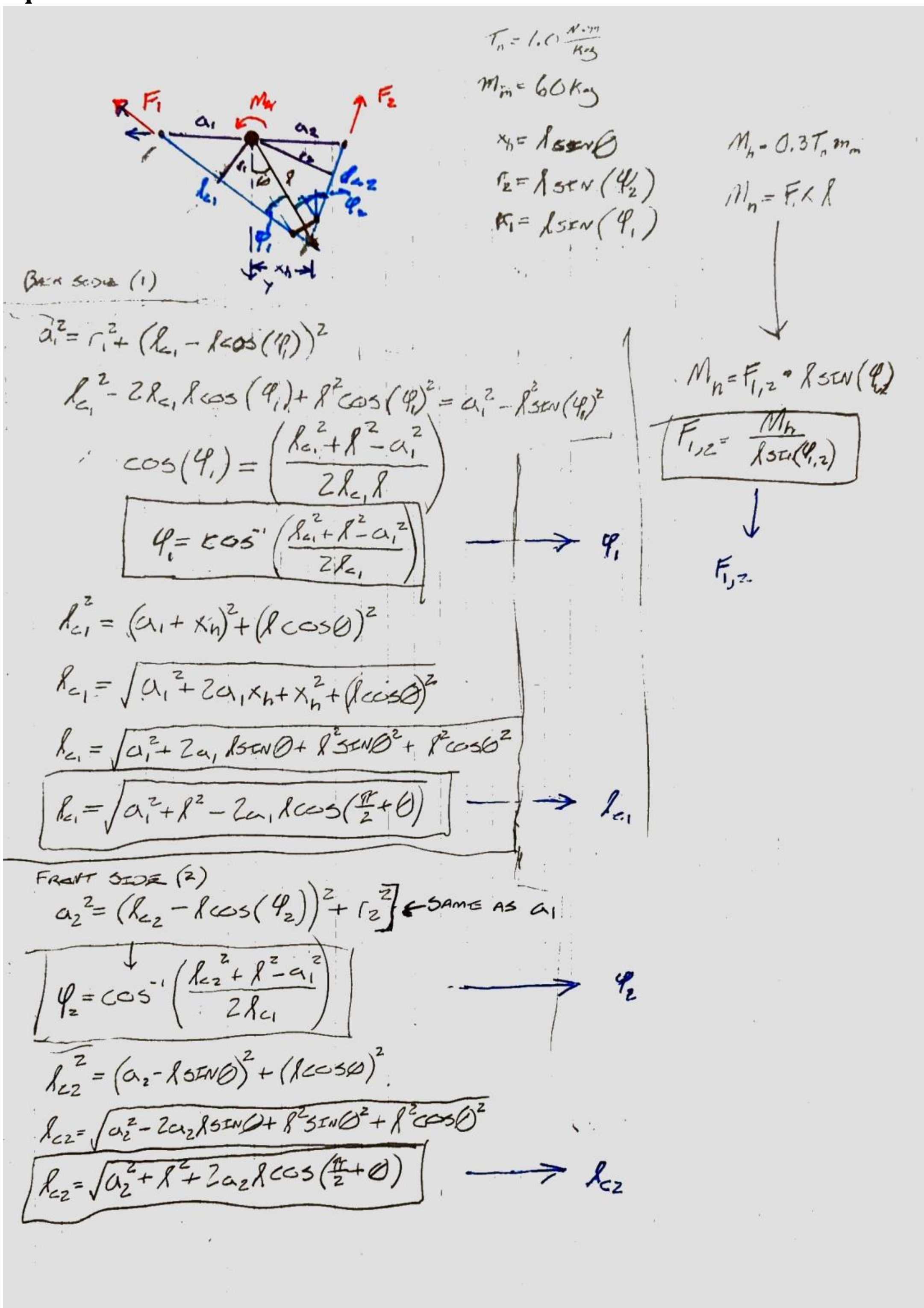

Figure 6.1 Hand calculations

6.2 MATLAB Code

```
close all
clear
clc

a_l = 0.2;                      %Lower proposed a value (m)
a_u = 0.4;                      %Upper proposed a value (m)
n = 3;                          %Number of values to test(a1,a2,front pulley, rear pulley)
M_Torque = 0.0497;              %Motor torque
r_pulley1 = linspace(0.015,0.025,n);    %
r_pulley2 = linspace(0.015,0.025,n);

tt = linspace(40,-12);          %Hip Angle relative to vertical

l = 0.25;                       %leg length from hip to cord distance (m)
m = 60;                         %Max expected mass (kg)
T_n = 1.0;                      %Peak natural torque (Nm/kg)
ar = linspace(a_l,a_u,n);       %x-dist.from hip of belt force
alpha = 0.2:0.6;                %Applied torque factor
Mh = alpha*T_n*m;               %Max applied hip moment

[a1,theta] = meshgrid(ar,tt);
a2 = meshgrid(ar,tt);

lc1 = sqrt(a1.^2+l^2-2.*a1.*l.*cos(pi/2+theta.*pi()./180));
lc2 = sqrt(a2.^2+l^2+2.*a2.*l.*cos(pi/2+theta.*pi()./180));
psi1 = acos((l^2+lc1.^2-a1.^2)./(2*l.*lc1));
psi2 = acos((l^2+lc2.^2-a2.^2)./(2*l.*lc2));
r1 = l.*sin(psi1);
r2 = l.*sin(psi2);

F1 = Mh./(l.*sin(psi1));
F2 = Mh./(l.*sin(psi2));

T1 = F1(1,:).*r_pulley1;
GR1 = T1./M_Torque;

T2 = F2(1,:).*r_pulley2;
GR2 = T2./M_Torque;

figure
plot(theta,F1,theta,F2);
legendCell = [strcat('a1 = ',string(num2cell(ar))),strcat('a2 = ',string(num2cell(ar)))];

legend(legendCell)
grid on
xlabel('Hip Angle (degrees)')
ylabel('Cord Force (N)')
title('Peak Force to Achieve Mh at Hip Angle')

figure
plot(theta,lc1,theta,lc2)
xlabel('Hip Anlge (degrees)')
ylabel('Length of Cord (m)')
grid on
title('Cord Length vs Hip Angle')
legend(legendCell)
```