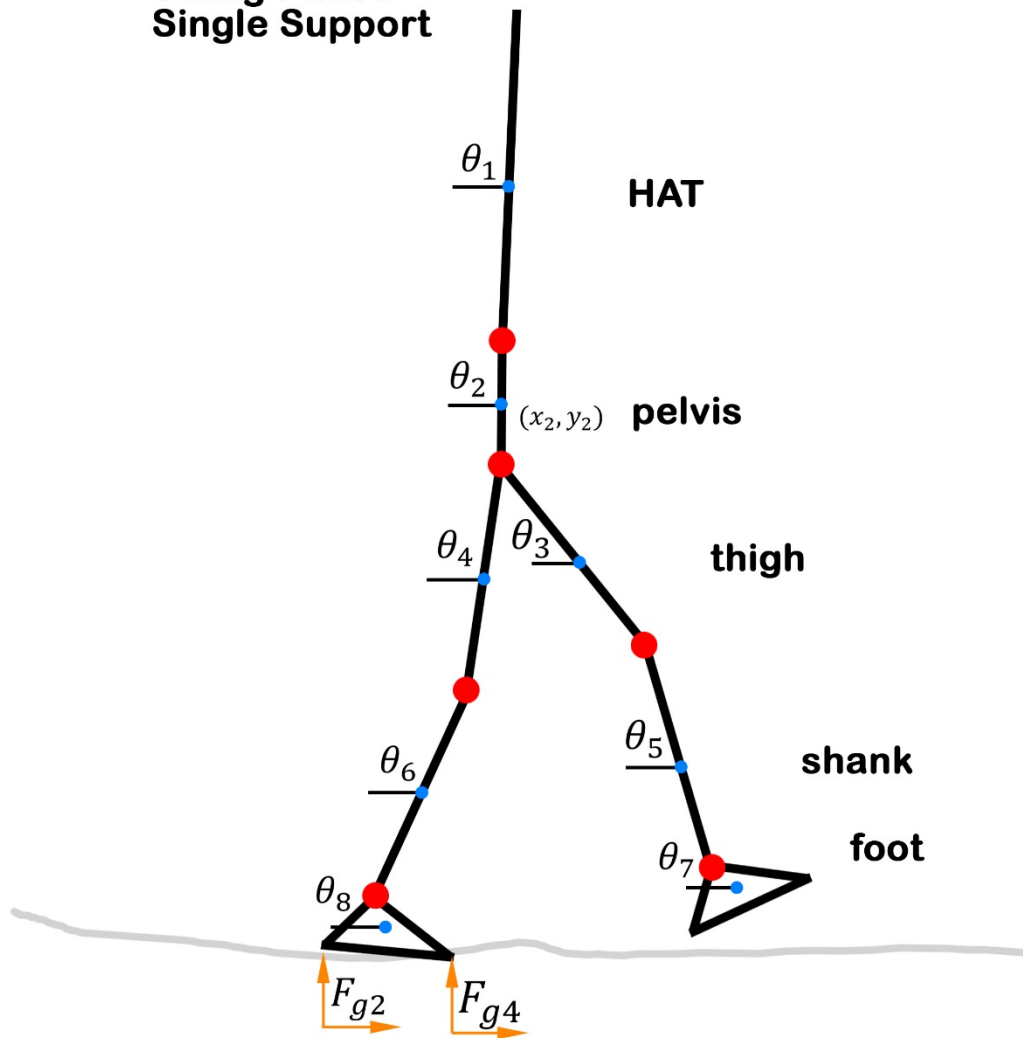
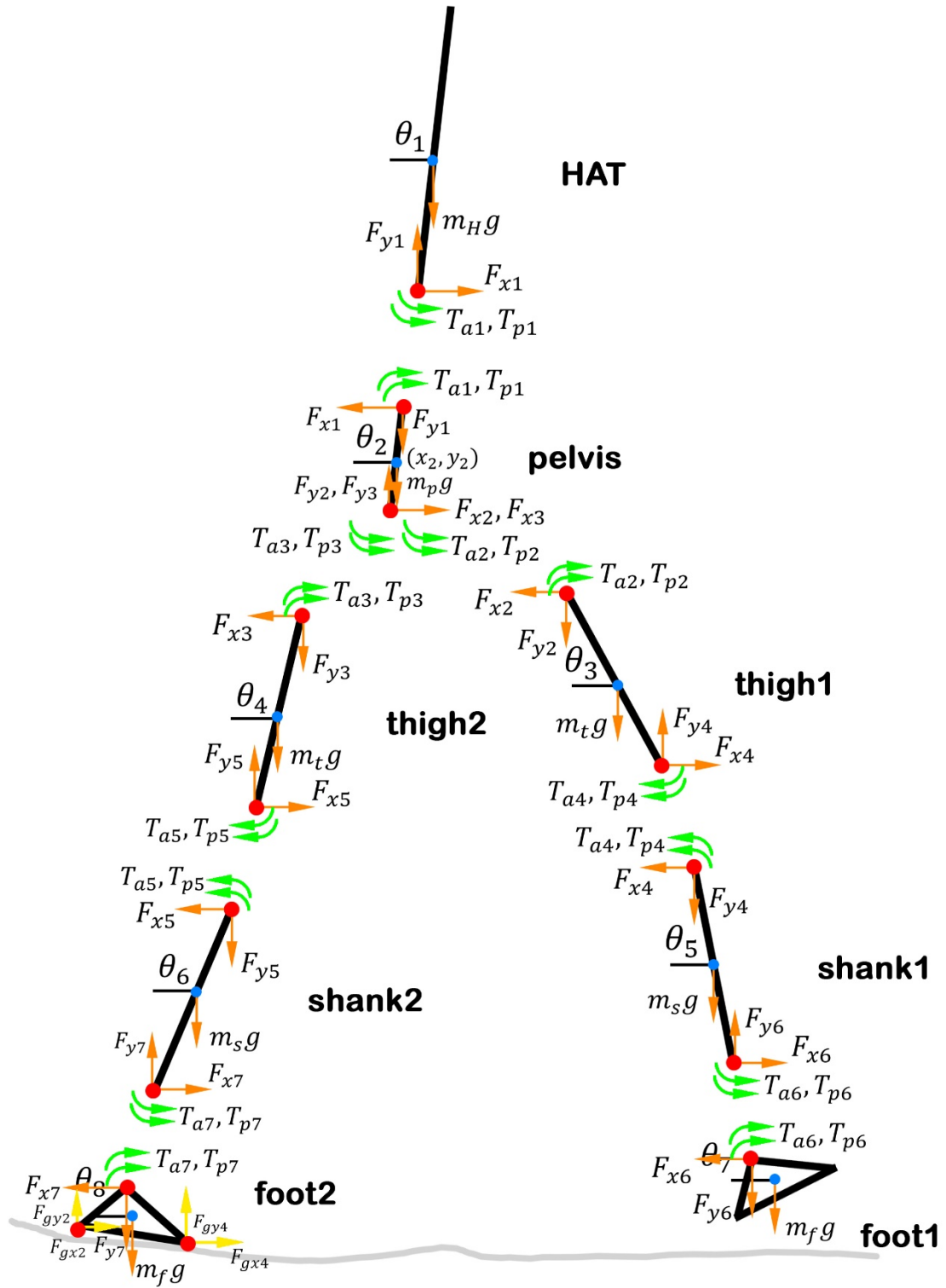


**Stage 6  
Swing Phase  
Single Support**



## Stage 6



## Stage 6

$$\mathbf{D}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{G} = \boldsymbol{\tau}$$

$$\begin{aligned} & \{[(m_H + m_p + 2m_t + 2m_s + 2m_f)\ddot{x}_2] + [m_H l_{H2} \sin \theta_1 \ddot{\theta}_1] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \sin \theta_2 \ddot{\theta}_2] \\ & + [(-m_t - 2m_s - 2m_f)l_t \sin \theta_3 \ddot{\theta}_3] + [(-m_t - 2m_s - 2m_f)l_t \sin \theta_4 \ddot{\theta}_4] \\ & + [(-m_s - 2m_f)l_s \sin \theta_5 \ddot{\theta}_5] + [(-m_s - 2m_f)l_s \sin \theta_6 \ddot{\theta}_6] + [-m_f l_{f1} \sin \theta_7 \ddot{\theta}_7] \\ & + [-m_f l_{f1} \sin \theta_8 \ddot{\theta}_8]\} + \{[m_H l_{H2} \cos \theta_1 \dot{\theta}_1^2] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 \dot{\theta}_2^2] \\ & + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_3 \dot{\theta}_3^2] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_4 \dot{\theta}_4^2] \\ & + [(-m_s - 2m_f)l_s \cos \theta_5 \dot{\theta}_5^2] + [(-m_s - 2m_f)l_s \cos \theta_6 \dot{\theta}_6^2] + [-m_f l_{f1} \cos \theta_7 \dot{\theta}_7^2] \\ & + [-m_f l_{f1} \cos \theta_8 \dot{\theta}_8^2]\} = F_{gx2} + F_{gx4} \end{aligned}$$

$$\begin{aligned} & \{[(m_H + m_p + 2m_t + 2m_s + 2m_f)\ddot{y}_2] + [m_H l_{H2} \cos \theta_1 \ddot{\theta}_1] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 \ddot{\theta}_2] \\ & + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_3 \ddot{\theta}_3] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_4 \ddot{\theta}_4] \\ & + [(-m_s - 2m_f)l_s \cos \theta_5 \ddot{\theta}_5] + [(-m_s - 2m_f)l_s \cos \theta_6 \ddot{\theta}_6] + [-m_f l_{f1} \cos \theta_7 \ddot{\theta}_7] \\ & + [-m_f l_{f1} \cos \theta_8 \ddot{\theta}_8]\} + \{[-m_H l_{H2} \sin \theta_1 \dot{\theta}_1^2] + [(-m_H + 2m_t + 2m_s + 2m_f)l_p \sin \theta_2 \dot{\theta}_2^2] \\ & + [(m_t + 2m_s + 2m_f)l_t \sin \theta_3 \dot{\theta}_3^2] + [(m_t + 2m_s + 2m_f)l_t \sin \theta_4 \dot{\theta}_4^2] \\ & + [(m_s + 2m_f)l_s \sin \theta_5 \dot{\theta}_5^2] + [(m_s + 2m_f)l_s \sin \theta_6 \dot{\theta}_6^2] + [m_f l_{f1} \sin \theta_7 \dot{\theta}_7^2] \\ & + [m_f l_{f1} \sin \theta_8 \dot{\theta}_8^2]\} + \{m_H g + m_p g + 2m_t g + 2m_s g + 2m_f g\} = F_{gy2} + F_{gy4} \end{aligned}$$

$$\begin{aligned} & \{[m_H l_{H2} \sin \theta_1 \ddot{x}_2] + [m_H l_{H2} \cos \theta_1 \ddot{y}_2] + [(I_H + m_H l_{H2}^2) \ddot{\theta}_1] + [m_H l_{H2} l_p \cos(\theta_1 - \theta_2) \ddot{\theta}_2]\} \\ & + \{[m_H l_{H2} l_p \sin(\theta_1 - \theta_2) \dot{\theta}_2^2] + T_{p1} + T_{a1}\} + \{m_H l_{H2} \cos \theta_1 g\} = 0 \end{aligned}$$

$$\begin{aligned} & \{[(m_H - 2m_t - 2m_s - 2m_f)l_p \sin \theta_2 \ddot{x}_2] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 \ddot{y}_2] \\ & + [m_H l_{H2} l_p \cos(\theta_1 - \theta_2) \ddot{\theta}_1] + [(I_p + m_H l_p^2 + 2m_t l_p^2 + 2m_s l_p^2 + 2m_f l_p^2) \ddot{\theta}_2] \\ & + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_3) \ddot{\theta}_3] \\ & + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_4) \ddot{\theta}_4] + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_5) \ddot{\theta}_5] \\ & + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_6) \ddot{\theta}_6] + [m_f l_p l_{f1} \cos(\theta_2 - \theta_7) \ddot{\theta}_7] \\ & + [m_f l_p l_{f1} \cos(\theta_2 - \theta_8) \ddot{\theta}_8]\} \\ & + \{[-m_H l_{H2} l_p \sin(\theta_1 - \theta_2) \dot{\theta}_1^2] + [(m_t + 2m_s + 2m_f)l_p l_t \sin(\theta_2 - \theta_3) \dot{\theta}_3^2] \\ & + [(m_t + 2m_s + 2m_f)l_p l_t \sin(\theta_2 - \theta_4) \dot{\theta}_4^2] + [(m_s + 2m_f)l_p l_s \sin(\theta_2 - \theta_5) \dot{\theta}_5^2] \\ & + [(m_s + 2m_f)l_p l_s \sin(\theta_2 - \theta_6) \dot{\theta}_6^2] + [m_f l_p l_{f1} \sin(\theta_2 - \theta_7) \dot{\theta}_7^2] \\ & + [m_f l_p l_{f1} \sin(\theta_2 - \theta_8) \dot{\theta}_8^2] - T_{p1} + T_{p2} + T_{p3} - T_{a1} + T_{a2} + T_{a3}\} \\ & + \{(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 g\} \\ & = -(F_{gx2} + F_{gx4})l_p \sin \theta_2 - (F_{gy2} + F_{gy4})l_p \cos \theta_2 \end{aligned}$$

$$\begin{aligned}
& \{ [(-m_t - 2m_s - 2m_f)l_t \sin \theta_3 \ddot{x}_2] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_3 \ddot{y}_2] \\
& + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_3) \ddot{\theta}_2] + [(I_t + m_t l_t^2 + 4m_s l_t^2 + 4m_f l_t^2) \ddot{\theta}_3] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_3 - \theta_5) \ddot{\theta}_5] + [2m_f l_t l_{f1} \cos(\theta_3 - \theta_7) \ddot{\theta}_7] \} \\
& + \left\{ [(-m_t - 2m_s - 2m_f)l_p l_t \sin(\theta_2 - \theta_3) \dot{\theta}_2^2] \right. \\
& + [(2m_s + 4m_f)l_t l_s \sin(\theta_3 - \theta_5) \dot{\theta}_5^2] + [2m_f l_t l_{f1} \sin(\theta_3 - \theta_7) \dot{\theta}_7^2] - T_{p2} - T_{p4} \\
& \left. - T_{s3} - T_{s5} \right\} + \{ (-m_t - 2m_s - 2m_f)l_t \cos \theta_3 g \} = 0
\end{aligned}$$

$$\begin{aligned}
& \{ [(-m_t - 2m_s - 2m_f)l_t \sin \theta_4 \ddot{x}_2] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_4 \ddot{y}_2] \\
& + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_4) \ddot{\theta}_2] + [(I_t + m_t l_t^2 + 4m_s l_t^2 + 4m_f l_t^2) \ddot{\theta}_4] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_4 - \theta_6) \ddot{\theta}_6] + [2m_f l_t l_{f1} \cos(\theta_4 - \theta_8) \ddot{\theta}_8] \} \\
& + \left\{ [(-m_t - 2m_s - 2m_f)l_p l_t \sin(\theta_2 - \theta_4) \dot{\theta}_2^2] \right. \\
& + [(2m_s + 4m_f)l_t l_s \sin(\theta_4 - \theta_6) \dot{\theta}_6^2] + [2m_f l_t l_{f1} \sin(\theta_4 - \theta_8) \dot{\theta}_8^2] - T_{p3} - T_{p5} \\
& \left. - T_{s4} - T_{s6} \right\} + \{ (-m_t - 2m_s - 2m_f)l_t \cos \theta_4 g \} \\
& = -2(F_{gx2} + F_{gx4})l_t \sin \theta_4 - 2(F_{gy2} + F_{gy4})l_t \cos \theta_4
\end{aligned}$$

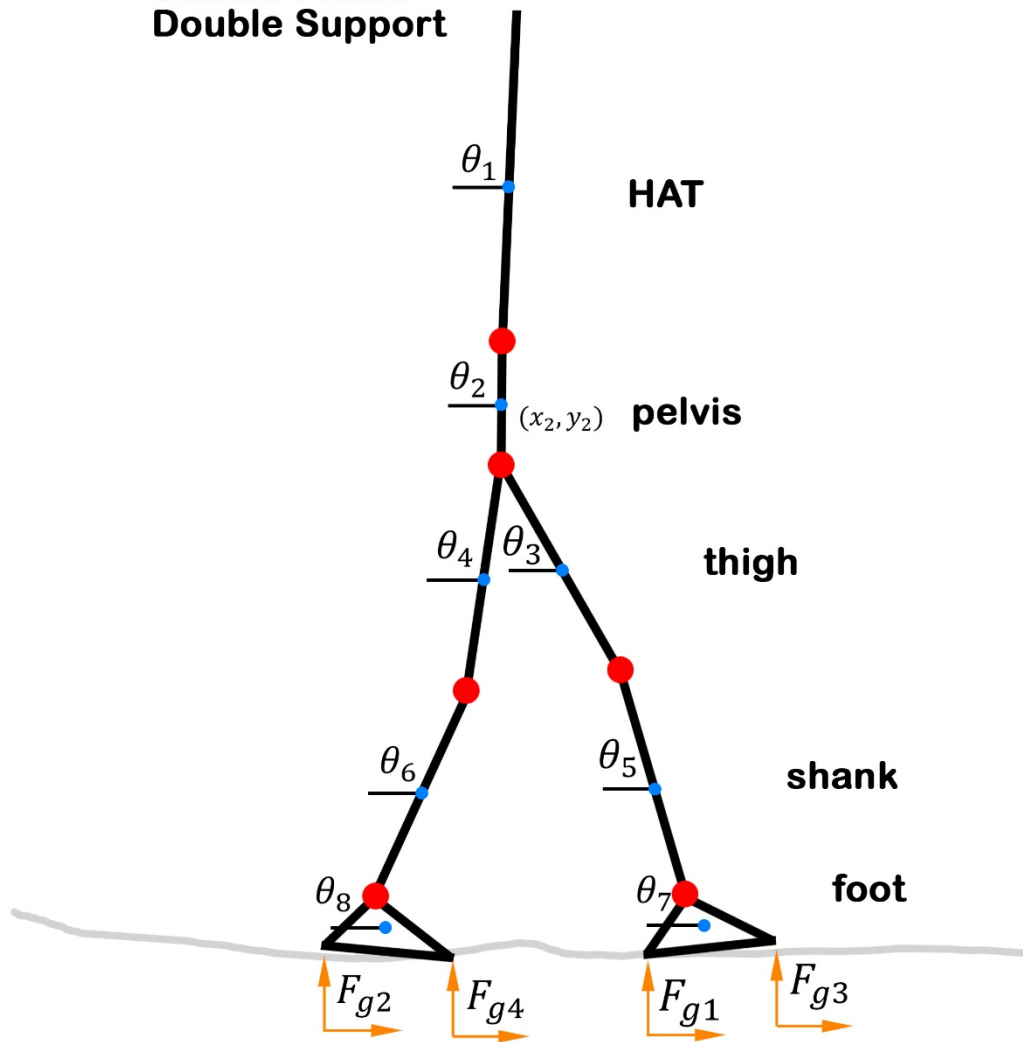
$$\begin{aligned}
& \{ [(-m_s - 2m_f)l_s \sin \theta_5 \ddot{x}_2] + [(-m_s - 2m_f)l_s \cos \theta_5 \ddot{y}_2] + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_5) \ddot{\theta}_2] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_3 - \theta_5) \ddot{\theta}_3] + [(I_s + m_s l_s^2 + 4m_f l_s^2) \ddot{\theta}_5] \\
& + [2m_f l_s l_{f1} \cos(\theta_5 - \theta_7) \ddot{\theta}_7] \} \\
& + \left\{ [(-m_s - 2m_f)l_p l_s \sin(\theta_2 - \theta_5) \dot{\theta}_2^2] + [(-2m_s - 4m_f)l_t l_s \sin(\theta_3 - \theta_5) \dot{\theta}_3^2] \right. \\
& + [2m_f l_s l_{f1} \sin(\theta_5 - \theta_7) \dot{\theta}_7^2] + T_{p4} + T_{p6} + T_{a4} + T_{a6} \left. \right\} \\
& + \{ (-m_s - 2m_f)l_s \cos \theta_5 g \} = 0
\end{aligned}$$

$$\begin{aligned}
& \{ [(-m_s - 2m_f)l_s \sin \theta_6 \ddot{x}_2] + [(-m_s - 2m_f)l_s \cos \theta_6 \ddot{y}_2] + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_6) \ddot{\theta}_2] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_4 - \theta_6) \ddot{\theta}_4] + [(I_s + m_s l_s^2 + 4m_f l_s^2) \ddot{\theta}_6] \\
& + [2m_f l_s l_{f1} \cos(\theta_6 - \theta_8) \ddot{\theta}_8] \} \\
& + \left\{ [(-m_s - 2m_f)l_p l_s \sin(\theta_2 - \theta_6) \dot{\theta}_2^2] + [(-2m_s - 4m_f)l_t l_s \sin(\theta_4 - \theta_6) \dot{\theta}_4^2] \right. \\
& + [2m_f l_s l_{f1} \sin(\theta_6 - \theta_8) \dot{\theta}_8^2] + T_{p5} + T_{p7} + T_{a5} + T_{a7} \left. \right\} \\
& + \{ (-m_s - 2m_f)l_s \cos \theta_6 g \} = -2(F_{gx2} + F_{gx4})l_s \sin \theta_6 - 2(F_{gy2} + F_{gy4})l_s \cos \theta_6
\end{aligned}$$

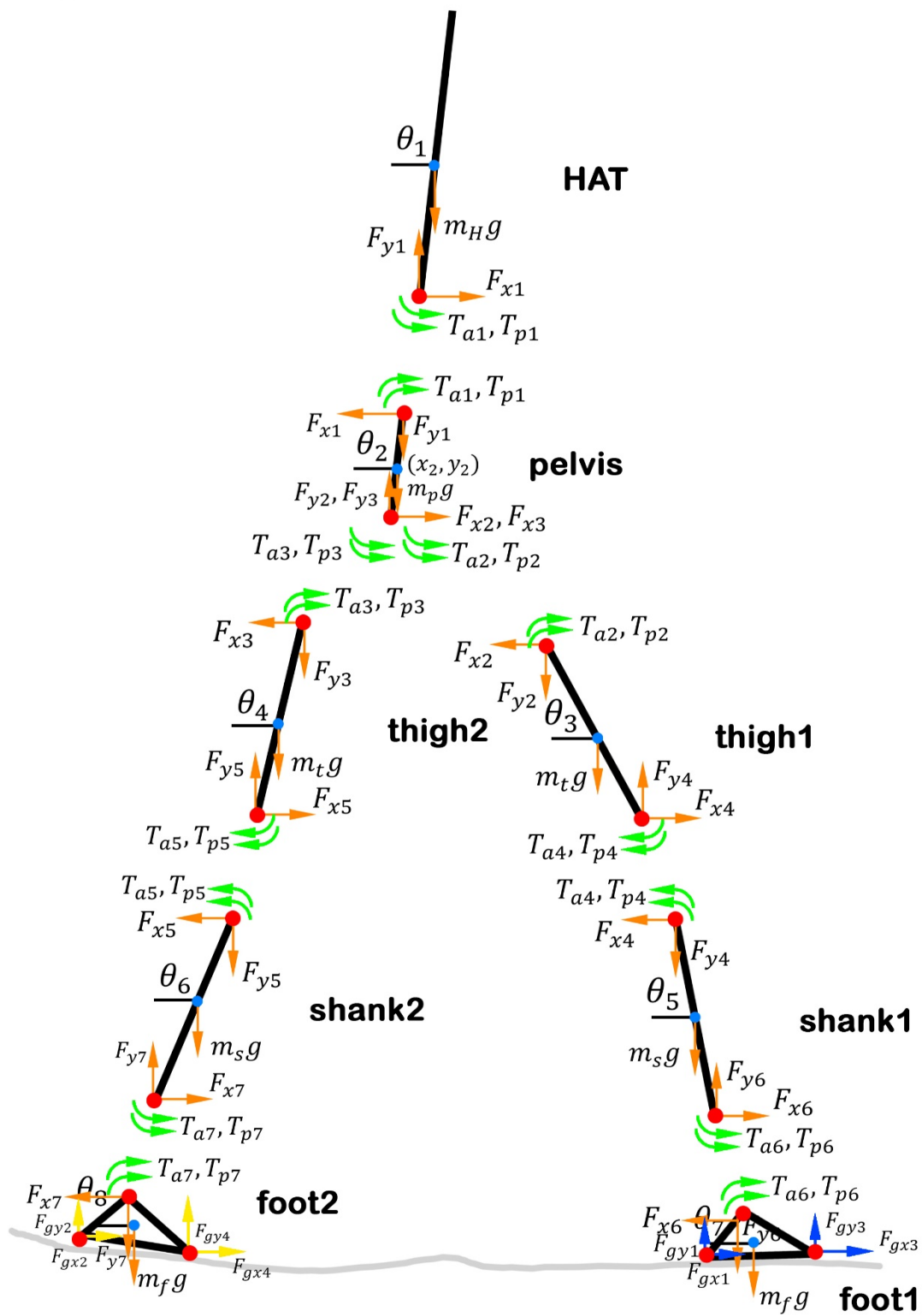
$$\begin{aligned}
& \{ [-m_f l_{f1} \sin \theta_7 \ddot{x}_2] + [-m_f l_{f1} \cos \theta_7 \ddot{y}_2] + [m_f l_p l_{f1} \cos(\theta_2 - \theta_7) \ddot{\theta}_2] + [2m_f l_t l_{f1} \cos(\theta_3 - \theta_7) \ddot{\theta}_3] \\
& + [2m_f l_s l_{f1} \cos(\theta_5 - \theta_7) \ddot{\theta}_5] + [(I_f + m_f l_{f1}^2) \ddot{\theta}_7] \} \\
& + \left\{ [-m_f l_p l_{f1} \sin(\theta_2 - \theta_7) \dot{\theta}_2^2] + [-2m_f l_t l_{f1} \sin(\theta_3 - \theta_7) \dot{\theta}_3^2] \right. \\
& + [-2m_f l_s l_{f1} \sin(\theta_5 - \theta_7) \dot{\theta}_5^2] - T_{p6} - T_{a6} \left. \right\} + \{ -m_f l_{f1} \cos \theta_7 g \} = 0
\end{aligned}$$

$$\begin{aligned}
& \{ [-m_f l_{f1} \sin \theta_8 \ddot{x}_2] + [-m_f l_{f1} \cos \theta_8 \ddot{y}_2] + [m_f l_p l_{f1} \cos(\theta_2 - \theta_8) \ddot{\theta}_2] + [2m_f l_t l_{f1} \cos(\theta_4 - \theta_8) \ddot{\theta}_4] \\
& \quad + [2m_f l_s l_{f1} \cos(\theta_6 - \theta_8) \ddot{\theta}_6] + [(I_f + m_f l_{f1}^2) \ddot{\theta}_8] \} \\
& + \left\{ \left[ -m_f l_p l_{f1} \sin(\theta_2 - \theta_8) \dot{\theta}_2^2 \right] + \left[ -2m_f l_t l_{f1} \sin(\theta_4 - \theta_8) \dot{\theta}_4^2 \right] \right. \\
& \quad \left. + \left[ -2m_f l_s l_{f1} \sin(\theta_6 - \theta_8) \dot{\theta}_6^2 \right] - \left[ \tau_{\theta 2} - \tau_{\theta 1} \right] \right\} + \{ -m_f l_{f1} \cos \theta_8 g \} \\
& = (l_{f1} \sin \theta_8 - l_{f2} \sin(\alpha_1 - \theta_8)) F_{gx2} + (l_{f1} \cos \theta_8 + l_{f2} \cos(\alpha_1 - \theta_8)) F_{gy2} \\
& + (l_{f1} \sin \theta_8 + l_{f3} \sin(\alpha_2 + \theta_8)) F_{gx4} + (l_{f1} \cos \theta_8 + l_{f3} \cos(\alpha_2 + \theta_8)) F_{gy4}
\end{aligned}$$

**Stage 1**  
**Stance Phase**  
**Double Support**



## Stage 1



## Stage 1

$$\mathbf{D}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{G} = \boldsymbol{\tau}$$

$$\begin{aligned} & \{[(m_H + m_p + 2m_t + 2m_s + 2m_f)\ddot{x}_2] + [m_H l_{H2} \sin \theta_1 \ddot{\theta}_1] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \sin \theta_2 \ddot{\theta}_2] \\ & + [(-m_t - 2m_s - 2m_f)l_t \sin \theta_3 \ddot{\theta}_3] + [(-m_t - 2m_s - 2m_f)l_t \sin \theta_4 \ddot{\theta}_4] \\ & + [(-m_s - 2m_f)l_s \sin \theta_5 \ddot{\theta}_5] + [(-m_s - 2m_f)l_s \sin \theta_6 \ddot{\theta}_6] + [-m_f l_{f1} \sin \theta_7 \ddot{\theta}_7] \\ & + [-m_f l_{f1} \sin \theta_8 \ddot{\theta}_8]\} + \{[m_H l_{H2} \cos \theta_1 \dot{\theta}_1^2] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 \dot{\theta}_2^2] \\ & + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_3 \dot{\theta}_3^2] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_4 \dot{\theta}_4^2] \\ & + [(-m_s - 2m_f)l_s \cos \theta_5 \dot{\theta}_5^2] + [(-m_s - 2m_f)l_s \cos \theta_6 \dot{\theta}_6^2] + [-m_f l_{f1} \cos \theta_7 \dot{\theta}_7^2] \\ & + [-m_f l_{f1} \cos \theta_8 \dot{\theta}_8^2]\} = F_{gx1} + F_{gx2} + F_{gx3} + F_{gx4} \end{aligned}$$

$$\begin{aligned} & \{[(m_H + m_p + 2m_t + 2m_s + 2m_f)\ddot{y}_2] + [m_H l_{H2} \cos \theta_1 \ddot{\theta}_1] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 \ddot{\theta}_2] \\ & + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_3 \ddot{\theta}_3] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_4 \ddot{\theta}_4] \\ & + [(-m_s - 2m_f)l_s \cos \theta_5 \ddot{\theta}_5] + [(-m_s - 2m_f)l_s \cos \theta_6 \ddot{\theta}_6] + [-m_f l_{f1} \cos \theta_7 \ddot{\theta}_7] \\ & + [-m_f l_{f1} \cos \theta_8 \ddot{\theta}_8]\} + \{[-m_H l_{H2} \sin \theta_1 \dot{\theta}_1^2] + [(-m_H + 2m_t + 2m_s + 2m_f)l_p \sin \theta_2 \dot{\theta}_2^2] \\ & + [(m_t + 2m_s + 2m_f)l_t \sin \theta_3 \dot{\theta}_3^2] + [(m_t + 2m_s + 2m_f)l_t \sin \theta_4 \dot{\theta}_4^2] \\ & + [(m_s + 2m_f)l_s \sin \theta_5 \dot{\theta}_5^2] + [(m_s + 2m_f)l_s \sin \theta_6 \dot{\theta}_6^2] + [m_f l_{f1} \sin \theta_7 \dot{\theta}_7^2] \\ & + [m_f l_{f1} \sin \theta_8 \dot{\theta}_8^2]\} + \{m_H g + m_p g + 2m_t g + 2m_s g + 2m_f g\} = F_{gy1} + F_{gy2} + F_{gy3} + F_{gy4} \end{aligned}$$

$$\begin{aligned} & \{[m_H l_{H2} \sin \theta_1 \ddot{x}_2] + [m_H l_{H2} \cos \theta_1 \ddot{y}_2] + [(I_H + m_H l_{H2}^2)\ddot{\theta}_1] + [m_H l_{H2} l_p \cos(\theta_1 - \theta_2) \ddot{\theta}_2]\} \\ & + \{[m_H l_{H2} l_p \sin(\theta_1 - \theta_2) \dot{\theta}_2^2] + T_{p1} + T_{p2}\} + \{m_H l_{H2} \cos \theta_1 g\} = 0 \end{aligned}$$

$$\begin{aligned} & \{[(m_H - 2m_t - 2m_s - 2m_f)l_p \sin \theta_2 \ddot{x}_2] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 \ddot{y}_2] \\ & + [m_H l_{H2} l_p \cos(\theta_1 - \theta_2) \ddot{\theta}_1] + [(I_p + m_H l_p^2 + 2m_t l_p^2 + 2m_s l_p^2 + 2m_f l_p^2)\ddot{\theta}_2] \\ & + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_3) \ddot{\theta}_3] \\ & + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_4) \ddot{\theta}_4] + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_5) \ddot{\theta}_5] \\ & + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_6) \ddot{\theta}_6] + [m_f l_p l_{f1} \cos(\theta_2 - \theta_7) \ddot{\theta}_7] \\ & + [m_f l_p l_{f1} \cos(\theta_2 - \theta_8) \ddot{\theta}_8]\} \\ & + \{[-m_H l_{H2} l_p \sin(\theta_1 - \theta_2) \dot{\theta}_1^2] + [(m_t + 2m_s + 2m_f)l_p l_t \sin(\theta_2 - \theta_3) \dot{\theta}_3^2] \\ & + [(m_t + 2m_s + 2m_f)l_p l_t \sin(\theta_2 - \theta_4) \dot{\theta}_4^2] + [(m_s + 2m_f)l_p l_s \sin(\theta_2 - \theta_5) \dot{\theta}_5^2] \\ & + [(m_s + 2m_f)l_p l_s \sin(\theta_2 - \theta_6) \dot{\theta}_6^2] + [m_f l_p l_{f1} \sin(\theta_2 - \theta_7) \dot{\theta}_7^2] \\ & + [m_f l_p l_{f1} \sin(\theta_2 - \theta_8) \dot{\theta}_8^2] - T_{p1} + T_{p2} + T_{p3} - T_{a1} + T_{a2} + T_{a3}\} \\ & + \{(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 g\} \\ & = -(F_{gx1} + F_{gx2} + F_{gx3} + F_{gx4})l_p \sin \theta_2 - (F_{gy1} + F_{gy2} + F_{gy3} + F_{gy4})l_p \cos \theta_2 \end{aligned}$$



$$\begin{aligned}
& \{ [(-m_t - 2m_s - 2m_f)l_t \sin \theta_3 \ddot{x}_2] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_3 \ddot{y}_2] \\
& + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_3) \ddot{\theta}_2] + [(I_t + m_t l_t^2 + 4m_s l_t^2 + 4m_f l_t^2) \ddot{\theta}_3] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_3 - \theta_5) \ddot{\theta}_5] + [2m_f l_t l_{f1} \cos(\theta_3 - \theta_7) \ddot{\theta}_7] \} \\
& + \left\{ [(-m_t - 2m_s - 2m_f)l_p l_t \sin(\theta_2 - \theta_3) \dot{\theta}_2^2] \right. \\
& + [(2m_s + 4m_f)l_t l_s \sin(\theta_3 - \theta_5) \dot{\theta}_5^2] + [2m_f l_t l_{f1} \sin(\theta_3 - \theta_7) \dot{\theta}_7^2] - T_{p2} - T_{p4} \\
& \left. - T_{s3} - T_{s5} \right\} + \{ (-m_t - 2m_s - 2m_f)l_t \cos \theta_3 g \} \\
& = -2(F_{gx1} + F_{gx3})l_t \sin \theta_3 - 2(F_{gy1} + F_{gy3})l_t \cos \theta_3
\end{aligned}$$

$$\begin{aligned}
& \{ [(-m_t - 2m_s - 2m_f)l_t \sin \theta_4 \ddot{x}_2] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_4 \ddot{y}_2] \\
& + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_4) \ddot{\theta}_2] + [(I_t + m_t l_t^2 + 4m_s l_t^2 + 4m_f l_t^2) \ddot{\theta}_4] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_4 - \theta_6) \ddot{\theta}_6] + [2m_f l_t l_{f1} \cos(\theta_4 - \theta_8) \ddot{\theta}_8] \} \\
& + \left\{ [(-m_t - 2m_s - 2m_f)l_p l_t \sin(\theta_2 - \theta_4) \dot{\theta}_2^2] \right. \\
& + [(2m_s + 4m_f)l_t l_s \sin(\theta_4 - \theta_6) \dot{\theta}_6^2] + [2m_f l_t l_{f1} \sin(\theta_4 - \theta_8) \dot{\theta}_8^2] - T_{p3} - T_{p5} \\
& \left. - T_{s3} - T_{s5} \right\} + \{ (-m_t - 2m_s - 2m_f)l_t \cos \theta_4 g \} \\
& = -2(F_{gx2} + F_{gx4})l_t \sin \theta_4 - 2(F_{gy2} + F_{gy4})l_t \cos \theta_4
\end{aligned}$$

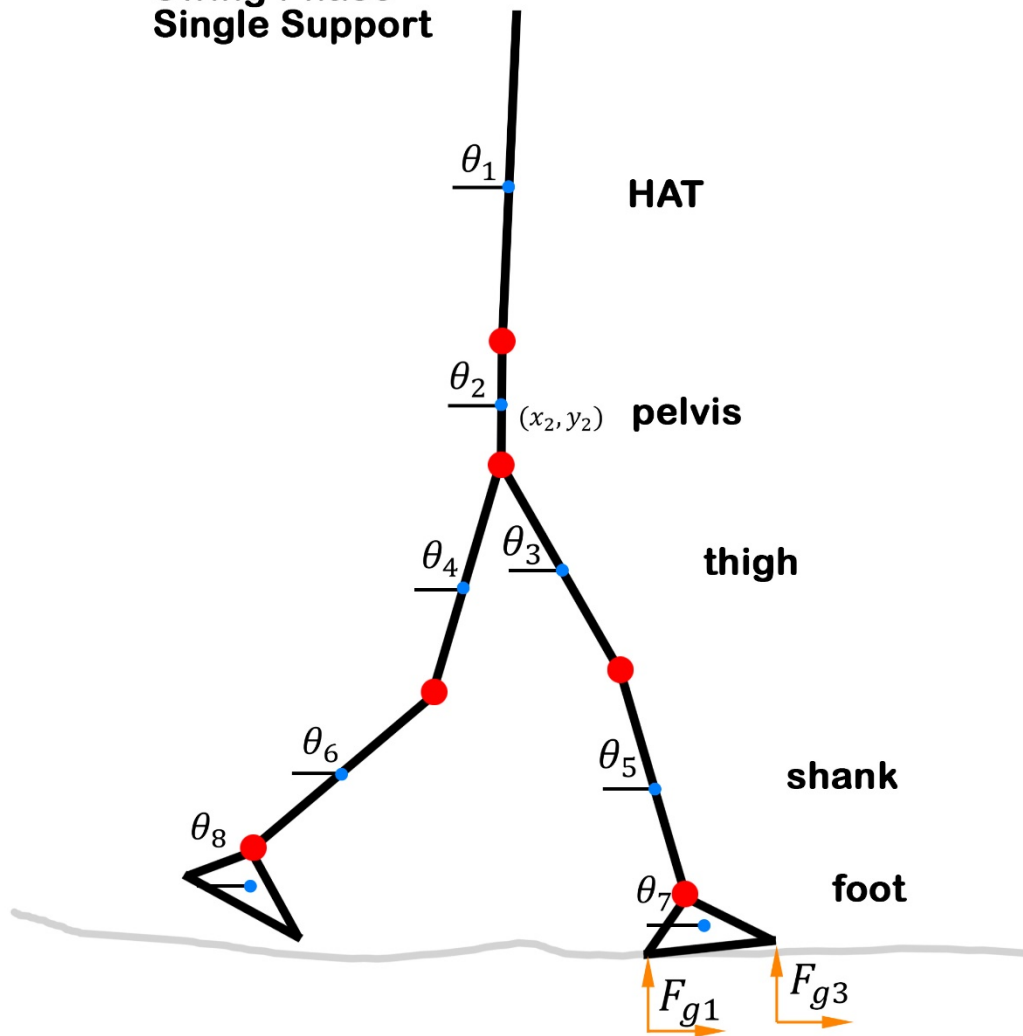
$$\begin{aligned}
& \{ [(-m_s - 2m_f)l_s \sin \theta_5 \ddot{x}_2] + [(-m_s - 2m_f)l_s \cos \theta_5 \ddot{y}_2] + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_5) \ddot{\theta}_2] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_3 - \theta_5) \ddot{\theta}_3] + [(I_s + m_s l_s^2 + 4m_f l_s^2) \ddot{\theta}_5] \\
& + [2m_f l_s l_{f1} \cos(\theta_5 - \theta_7) \ddot{\theta}_7] \} \\
& + \left\{ [(-m_s - 2m_f)l_p l_s \sin(\theta_2 - \theta_5) \dot{\theta}_2^2] + [(-2m_s - 4m_f)l_t l_s \sin(\theta_3 - \theta_5) \dot{\theta}_3^2] \right. \\
& + [2m_f l_s l_{f1} \sin(\theta_5 - \theta_7) \dot{\theta}_7^2] + T_{p4} + T_{p6} + T_{a4} + T_{a6} \left. \right\} \\
& + \{ (-m_s - 2m_f)l_s \cos \theta_5 g \} = -2(F_{gx1} + F_{gx3})l_s \sin \theta_5 - 2(F_{gy1} + F_{gy3})l_s \cos \theta_5
\end{aligned}$$

$$\begin{aligned}
& \{ [(-m_s - 2m_f)l_s \sin \theta_6 \ddot{x}_2] + [(-m_s - 2m_f)l_s \cos \theta_6 \ddot{y}_2] + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_6) \ddot{\theta}_2] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_4 - \theta_6) \ddot{\theta}_4] + [(I_s + m_s l_s^2 + 4m_f l_s^2) \ddot{\theta}_6] \\
& + [2m_f l_s l_{f1} \cos(\theta_6 - \theta_8) \ddot{\theta}_8] \} \\
& + \left\{ [(-m_s - 2m_f)l_p l_s \sin(\theta_2 - \theta_6) \dot{\theta}_2^2] + [(-2m_s - 4m_f)l_t l_s \sin(\theta_4 - \theta_6) \dot{\theta}_4^2] \right. \\
& + [2m_f l_s l_{f1} \sin(\theta_6 - \theta_8) \dot{\theta}_8^2] + T_{p5} + T_{p7} + T_{a5} + T_{a7} \left. \right\} \\
& + \{ (-m_s - 2m_f)l_s \cos \theta_6 g \} = -2(F_{gx2} + F_{gx4})l_s \sin \theta_6 - 2(F_{gy2} + F_{gy4})l_s \cos \theta_6
\end{aligned}$$

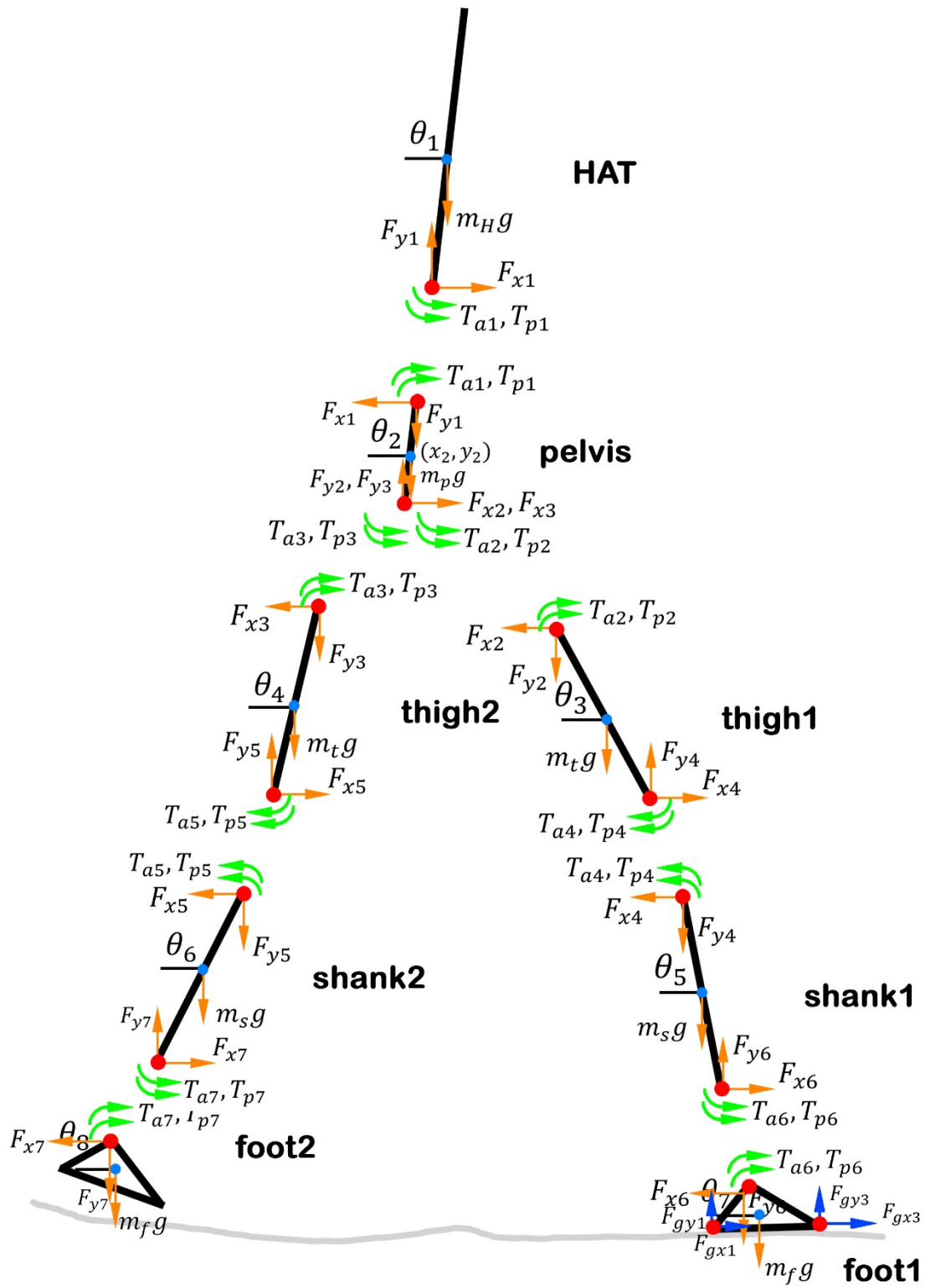
$$\begin{aligned}
& \{[-m_f l_{f1} \sin \theta_7 \ddot{x}_2] + [-m_f l_{f1} \cos \theta_7 \ddot{y}_2] + [m_f l_p l_{f1} \cos(\theta_2 - \theta_7) \ddot{\theta}_2] + [2m_f l_t l_{f1} \cos(\theta_3 - \theta_7) \ddot{\theta}_3] \\
& + [2m_f l_s l_{f1} \cos(\theta_5 - \theta_7) \ddot{\theta}_5] + [(I_f + m_f l_{f1}^2) \ddot{\theta}_7]\} \\
& + \left\{ \left[ -m_f l_p l_{f1} \sin(\theta_2 - \theta_7) \dot{\theta}_2^2 \right] + \left[ -2m_f l_t l_{f1} \sin(\theta_3 - \theta_7) \dot{\theta}_3^2 \right] \right. \\
& + \left. \left[ -2m_f l_s l_{f1} \sin(\theta_5 - \theta_7) \dot{\theta}_5^2 \right] - \left[ T_{\text{rot}} - T_{\text{rot}} \right] + \left\{ -m_f l_{f1} \cos \theta_7 g \right\} \right\} \\
& = (l_{f1} \sin \theta_7 - l_{f2} \sin(\alpha_1 - \theta_7)) F_{gx1} + (l_{f1} \cos \theta_7 + l_{f2} \cos(\alpha_1 - \theta_7)) F_{gy1} \\
& + (l_{f1} \sin \theta_7 + l_{f3} \sin(\alpha_2 + \theta_7)) F_{gx3} + (l_{f1} \cos \theta_7 + l_{f3} \cos(\alpha_2 + \theta_7)) F_{gy3}
\end{aligned}$$

$$\begin{aligned}
& \{[-m_f l_{f1} \sin \theta_8 \ddot{x}_2] + [-m_f l_{f1} \cos \theta_8 \ddot{y}_2] + [m_f l_p l_{f1} \cos(\theta_2 - \theta_8) \ddot{\theta}_2] + [2m_f l_t l_{f1} \cos(\theta_4 - \theta_8) \ddot{\theta}_4] \\
& + [2m_f l_s l_{f1} \cos(\theta_6 - \theta_8) \ddot{\theta}_6] + [(I_f + m_f l_{f1}^2) \ddot{\theta}_8]\} \\
& + \left\{ \left[ -m_f l_p l_{f1} \sin(\theta_2 - \theta_8) \dot{\theta}_2^2 \right] + \left[ -2m_f l_t l_{f1} \sin(\theta_4 - \theta_8) \dot{\theta}_4^2 \right] \right. \\
& + \left. \left[ -2m_f l_s l_{f1} \sin(\theta_6 - \theta_8) \dot{\theta}_6^2 \right] - \left[ T_{\text{rot}} - T_{\text{rot}} \right] + \left\{ -m_f l_{f1} \cos \theta_8 g \right\} \right\} \\
& = (l_{f1} \sin \theta_8 - l_{f2} \sin(\alpha_1 - \theta_8)) F_{gx2} + (l_{f1} \cos \theta_8 + l_{f2} \cos(\alpha_1 - \theta_8)) F_{gy2} \\
& + (l_{f1} \sin \theta_8 + l_{f3} \sin(\alpha_2 + \theta_8)) F_{gx4} + (l_{f1} \cos \theta_8 + l_{f3} \cos(\alpha_2 + \theta_8)) F_{gy4}
\end{aligned}$$

**Stage 2  
Swing Phase  
Single Support**



## Stage 2



## Stage 2

$$\mathbf{D}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{G} = \boldsymbol{\tau}$$

$$\begin{aligned} & \{[(m_H + m_p + 2m_t + 2m_s + 2m_f)\ddot{x}_2] + [m_H l_{H2} \sin \theta_1 \ddot{\theta}_1] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \sin \theta_2 \ddot{\theta}_2] \\ & + [(-m_t - 2m_s - 2m_f)l_t \sin \theta_3 \ddot{\theta}_3] + [(-m_t - 2m_s - 2m_f)l_t \sin \theta_4 \ddot{\theta}_4] \\ & + [(-m_s - 2m_f)l_s \sin \theta_5 \ddot{\theta}_5] + [(-m_s - 2m_f)l_s \sin \theta_6 \ddot{\theta}_6] + [-m_f l_{f1} \sin \theta_7 \ddot{\theta}_7] \\ & + [-m_f l_{f1} \sin \theta_8 \ddot{\theta}_8]\} + \{[m_H l_{H2} \cos \theta_1 \dot{\theta}_1^2] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 \dot{\theta}_2^2] \\ & + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_3 \dot{\theta}_3^2] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_4 \dot{\theta}_4^2] \\ & + [(-m_s - 2m_f)l_s \cos \theta_5 \dot{\theta}_5^2] + [(-m_s - 2m_f)l_s \cos \theta_6 \dot{\theta}_6^2] + [-m_f l_{f1} \cos \theta_7 \dot{\theta}_7^2] \\ & + [-m_f l_{f1} \cos \theta_8 \dot{\theta}_8^2]\} = F_{gx1} + F_{gx3} \end{aligned}$$

$$\begin{aligned} & \{[(m_H + m_p + 2m_t + 2m_s + 2m_f)\ddot{y}_2] + [m_H l_{H2} \cos \theta_1 \ddot{\theta}_1] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 \ddot{\theta}_2] \\ & + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_3 \ddot{\theta}_3] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_4 \ddot{\theta}_4] \\ & + [(-m_s - 2m_f)l_s \cos \theta_5 \ddot{\theta}_5] + [(-m_s - 2m_f)l_s \cos \theta_6 \ddot{\theta}_6] + [-m_f l_{f1} \cos \theta_7 \ddot{\theta}_7] \\ & + [-m_f l_{f1} \cos \theta_8 \ddot{\theta}_8]\} + \{[-m_H l_{H2} \sin \theta_1 \dot{\theta}_1^2] + [(-m_H + 2m_t + 2m_s + 2m_f)l_p \sin \theta_2 \dot{\theta}_2^2] \\ & + [(m_t + 2m_s + 2m_f)l_t \sin \theta_3 \dot{\theta}_3^2] + [(m_t + 2m_s + 2m_f)l_t \sin \theta_4 \dot{\theta}_4^2] \\ & + [(m_s + 2m_f)l_s \sin \theta_5 \dot{\theta}_5^2] + [(m_s + 2m_f)l_s \sin \theta_6 \dot{\theta}_6^2] + [m_f l_{f1} \sin \theta_7 \dot{\theta}_7^2] \\ & + [m_f l_{f1} \sin \theta_8 \dot{\theta}_8^2]\} + \{m_H g + m_p g + 2m_t g + 2m_s g + 2m_f g\} = F_{gy1} + F_{gy3} \end{aligned}$$

$$\begin{aligned} & \{[m_H l_{H2} \sin \theta_1 \ddot{x}_2] + [m_H l_{H2} \cos \theta_1 \ddot{y}_2] + [(I_H + m_H l_{H2}^2)\ddot{\theta}_1] + [m_H l_{H2} l_p \cos(\theta_1 - \theta_2) \ddot{\theta}_2]\} \\ & + \{[m_H l_{H2} l_p \sin(\theta_1 - \theta_2) \dot{\theta}_2^2] + T_{p1} + T_{p3}\} + \{m_H l_{H2} \cos \theta_1 g\} = 0 \end{aligned}$$

$$\begin{aligned} & \{[(m_H - 2m_t - 2m_s - 2m_f)l_p \sin \theta_2 \ddot{x}_2] + [(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 \ddot{y}_2] \\ & + [m_H l_{H2} l_p \cos(\theta_1 - \theta_2) \ddot{\theta}_1] + [(I_p + m_H l_p^2 + 2m_t l_p^2 + 2m_s l_p^2 + 2m_f l_p^2)\ddot{\theta}_2] \\ & + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_3) \ddot{\theta}_3] \\ & + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_4) \ddot{\theta}_4] + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_5) \ddot{\theta}_5] \\ & + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_6) \ddot{\theta}_6] + [m_f l_p l_{f1} \cos(\theta_2 - \theta_7) \ddot{\theta}_7] \\ & + [m_f l_p l_{f1} \cos(\theta_2 - \theta_8) \ddot{\theta}_8]\} \\ & + \{[-m_H l_{H2} l_p \sin(\theta_1 - \theta_2) \dot{\theta}_1^2] + [(m_t + 2m_s + 2m_f)l_p l_t \sin(\theta_2 - \theta_3) \dot{\theta}_3^2] \\ & + [(m_t + 2m_s + 2m_f)l_p l_t \sin(\theta_2 - \theta_4) \dot{\theta}_4^2] + [(m_s + 2m_f)l_p l_s \sin(\theta_2 - \theta_5) \dot{\theta}_5^2] \\ & + [(m_s + 2m_f)l_p l_s \sin(\theta_2 - \theta_6) \dot{\theta}_6^2] + [m_f l_p l_{f1} \sin(\theta_2 - \theta_7) \dot{\theta}_7^2] \\ & + [m_f l_p l_{f1} \sin(\theta_2 - \theta_8) \dot{\theta}_8^2] - T_{p1} + T_{p2} + T_{p3} - T_{a1} + T_{a2} + T_{a3}\} \\ & + \{(m_H - 2m_t - 2m_s - 2m_f)l_p \cos \theta_2 g\} \\ & = -(F_{gx1} + F_{gx3})l_p \sin \theta_2 - (F_{gy1} + F_{gy3})l_p \cos \theta_2 \end{aligned}$$

$$\begin{aligned}
& \{ [(-m_t - 2m_s - 2m_f)l_t \sin \theta_3 \ddot{x}_2] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_3 \ddot{y}_2] \\
& + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_3) \ddot{\theta}_2] + [(I_t + m_t l_t^2 + 4m_s l_t^2 + 4m_f l_t^2) \ddot{\theta}_3] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_3 - \theta_5) \ddot{\theta}_5] + [2m_f l_t l_{f1} \cos(\theta_3 - \theta_7) \ddot{\theta}_7] \} \\
& + \left\{ [(-m_t - 2m_s - 2m_f)l_p l_t \sin(\theta_2 - \theta_3) \dot{\theta}_2^2] \right. \\
& + [(2m_s + 4m_f)l_t l_s \sin(\theta_3 - \theta_5) \dot{\theta}_5^2] + [2m_f l_t l_{f1} \sin(\theta_3 - \theta_7) \dot{\theta}_7^2] - T_{p2} - T_{p4} \\
& \left. - T_{s3} - T_{s5} \right\} + \{ (-m_t - 2m_s - 2m_f)l_t \cos \theta_3 g \} \\
& = -2(F_{gx1} + F_{gx3})l_t \sin \theta_3 - 2(F_{gy1} + F_{gy3})l_t \cos \theta_3
\end{aligned}$$

$$\begin{aligned}
& \{ [(-m_t - 2m_s - 2m_f)l_t \sin \theta_4 \ddot{x}_2] + [(-m_t - 2m_s - 2m_f)l_t \cos \theta_4 \ddot{y}_2] \\
& + [(m_t + 2m_s + 2m_f)l_p l_t \cos(\theta_2 - \theta_4) \ddot{\theta}_2] + [(I_t + m_t l_t^2 + 4m_s l_t^2 + 4m_f l_t^2) \ddot{\theta}_4] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_4 - \theta_6) \ddot{\theta}_6] + [2m_f l_t l_{f1} \cos(\theta_4 - \theta_8) \ddot{\theta}_8] \} \\
& + \left\{ [(-m_t - 2m_s - 2m_f)l_p l_t \sin(\theta_2 - \theta_4) \dot{\theta}_2^2] \right. \\
& + [(2m_s + 4m_f)l_t l_s \sin(\theta_4 - \theta_6) \dot{\theta}_6^2] + [2m_f l_t l_{f1} \sin(\theta_4 - \theta_8) \dot{\theta}_8^2] - T_{p3} - T_{p5} \\
& \left. - T_{s3} - T_{s5} \right\} + \{ (-m_t - 2m_s - 2m_f)l_t \cos \theta_4 g \} = 0
\end{aligned}$$

$$\begin{aligned}
& \{ [(-m_s - 2m_f)l_s \sin \theta_5 \ddot{x}_2] + [(-m_s - 2m_f)l_s \cos \theta_5 \ddot{y}_2] + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_5) \ddot{\theta}_2] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_3 - \theta_5) \ddot{\theta}_3] + [(I_s + m_s l_s^2 + 4m_f l_s^2) \ddot{\theta}_5] \\
& + [2m_f l_s l_{f1} \cos(\theta_5 - \theta_7) \ddot{\theta}_7] \} \\
& + \left\{ [(-m_s - 2m_f)l_p l_s \sin(\theta_2 - \theta_5) \dot{\theta}_2^2] + [(-2m_s - 4m_f)l_t l_s \sin(\theta_3 - \theta_5) \dot{\theta}_3^2] \right. \\
& + [2m_f l_s l_{f1} \sin(\theta_5 - \theta_7) \dot{\theta}_7^2] + T_{p4} + T_{p6} + T_{s3} + T_{s5} \left. \right\} \\
& + \{ (-m_s - 2m_f)l_s \cos \theta_5 g \} = -2(F_{gx1} + F_{gx3})l_s \sin \theta_5 - 2(F_{gy1} + F_{gy3})l_s \cos \theta_5
\end{aligned}$$

$$\begin{aligned}
& \{ [(-m_s - 2m_f)l_s \sin \theta_6 \ddot{x}_2] + [(-m_s - 2m_f)l_s \cos \theta_6 \ddot{y}_2] + [(m_s + 2m_f)l_p l_s \cos(\theta_2 - \theta_6) \ddot{\theta}_2] \\
& + [(2m_s + 4m_f)l_t l_s \cos(\theta_4 - \theta_6) \ddot{\theta}_4] + [(I_s + m_s l_s^2 + 4m_f l_s^2) \ddot{\theta}_6] \\
& + [2m_f l_s l_{f1} \cos(\theta_6 - \theta_8) \ddot{\theta}_8] \} \\
& + \left\{ [(-m_s - 2m_f)l_p l_s \sin(\theta_2 - \theta_6) \dot{\theta}_2^2] + [(-2m_s - 4m_f)l_t l_s \sin(\theta_4 - \theta_6) \dot{\theta}_4^2] \right. \\
& + [2m_f l_s l_{f1} \sin(\theta_6 - \theta_8) \dot{\theta}_8^2] + T_{p5} + T_{p7} + T_{s3} + T_{s7} \left. \right\} \\
& + \{ (-m_s - 2m_f)l_s \cos \theta_6 g \} = 0
\end{aligned}$$

$$\begin{aligned}
& \{ [-m_f l_{f1} \sin \theta_7 \ddot{x}_2] + [-m_f l_{f1} \cos \theta_7 \ddot{y}_2] + [m_f l_p l_{f1} \cos(\theta_2 - \theta_7) \ddot{\theta}_2] + [2m_f l_t l_{f1} \cos(\theta_3 - \theta_7) \ddot{\theta}_3] \\
& + [2m_f l_s l_{f1} \cos(\theta_5 - \theta_7) \ddot{\theta}_5] + [(I_f + m_f l_{f1}^2) \ddot{\theta}_7] \} \\
& + \left\{ [-m_f l_p l_{f1} \sin(\theta_2 - \theta_7) \dot{\theta}_2^2] + [-2m_f l_t l_{f1} \sin(\theta_3 - \theta_7) \dot{\theta}_3^2] \right. \\
& + [-2m_f l_s l_{f1} \sin(\theta_5 - \theta_7) \dot{\theta}_5^2] - T_{p6} - T_{s6} \left. \right\} + \{ -m_f l_{f1} \cos \theta_7 g \} \\
& = (l_{f1} \sin \theta_7 - l_{f2} \sin(\alpha_1 - \theta_7))F_{gx1} + (l_{f1} \cos \theta_7 + l_{f2} \cos(\alpha_1 - \theta_7))F_{gy1} \\
& + (l_{f1} \sin \theta_7 + l_{f3} \sin(\alpha_2 + \theta_7))F_{gx3} + (l_{f1} \cos \theta_7 + l_{f3} \cos(\alpha_2 + \theta_7))F_{gy3}
\end{aligned}$$

$$\begin{aligned}
& \{ [-m_f l_{f1} \sin \theta_8 \ddot{x}_2] + [-m_f l_{f1} \cos \theta_8 \ddot{y}_2] + [m_f l_p l_{f1} \cos(\theta_2 - \theta_8) \ddot{\theta}_2] + [2m_f l_t l_{f1} \cos(\theta_4 - \theta_8) \ddot{\theta}_4] \\
& \quad + [2m_f l_s l_{f1} \cos(\theta_6 - \theta_8) \ddot{\theta}_6] + [(I_f + m_f l_{f1}^2) \ddot{\theta}_8] \} \\
& + \left\{ \left[ -m_f l_p l_{f1} \sin(\theta_2 - \theta_8) \dot{\theta}_2^2 \right] + \left[ -2m_f l_t l_{f1} \sin(\theta_4 - \theta_8) \dot{\theta}_4^2 \right] \right. \\
& \quad \left. + \left[ -2m_f l_s l_{f1} \sin(\theta_6 - \theta_8) \dot{\theta}_6^2 \right] - \boxed{T_{p2}} - \boxed{T_{s2}} \right\} + \{ -m_f l_{f1} \cos \theta_8 g \} = 0
\end{aligned}$$