Strategy to lock the knee of exoskeleton stance leg: study in the framework of ballistic walking model

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Motivation

- To design a wearable assist device for human.
  - To improve daily life for patients or elderly
  - To avoid the musculoskeletal disorders for industrial workers

Desired performances:

- To be able to compensate a part of the loads due the human's weight.
- To have an assist device with an energetic autonomy.
- Good adaptation to the shape of human's body.

Statement of the problem

- To consider a five-link planar Biped with a strapped exoskeleton.
- There are not any actuators in our exoskeleton.
- To define a ballistic walking gait of the biped alone without any assist device for the transport of a load.
- During ballistic walking of the biped with exoskeleton the knee of the stance leg of the exoskeleton (and as a consequence of the biped) is locked.
- Walking of the biped consists of alternating single- and instantaneous double-support phases.
- At the instant of this phase, the knee of the previous swing leg is locked and the knee of the previous stance leg is unlocked.
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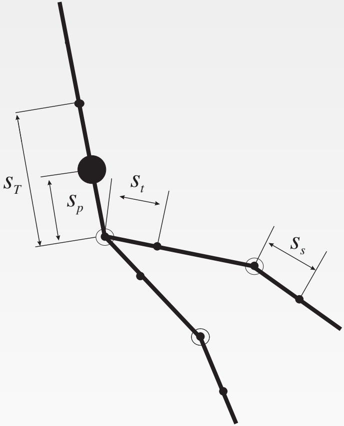
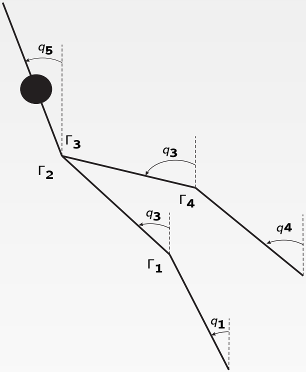
The geometrical structure of the biped and its wearable assist device.



(a)



(b)

- seven generalized coordinates $\mathbf{x} = [q_1, q_2, q_3, q_4, q_5, x, y]^\top$.

Physical parameters.

	Mass (kg)	Length (m)	Inertia moment ($kg \cdot m^2$)	center of mass (m)
Human shin	$m_s = 4.6$	$l_s = 0.55$	$I^s = 0.0521$	$s_s = 0.324$
Human thigh	$m_t = 8.6$	$l_t = 0.45$	$I^t = 0.75$	$s_t = 0.18$
Human trunk	$m_T = 48.6$	$l_T = 0.75$	$I^T = 11.3$	$s_T = 0.386$
Exoskeleton shin	$m_1 = 1.0$	$l_1 = 0.497$	$I^1 = 0.0260$	$s_s = 0.324$
Exoskeleton thigh	$m_2 = 2.0$	$l_2 = 0.41$	$I^2 = 0.0354$	$s_t = 0.18$
Exoskeleton trunk	$m_3 = 8.0$	$l_3 = 0.75$	$I^3 = 0.3817$	$s_T = 0.386$

Matrix equations

Equations of the motion of the biped in single support

$$\mathbf{A}(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{h}(\mathbf{x}, \dot{\mathbf{x}}) = \mathbf{D}\Gamma + \mathbf{J}_{\mathbf{r}_1}^{\top}\mathbf{r}_1 + \mathbf{J}_{\mathbf{r}_2}^{\top}\mathbf{r}_2, \quad (1)$$

with the constraint equations,

$$\mathbf{J}_{\mathbf{r}_i}\ddot{\mathbf{x}} + \dot{\mathbf{J}}_{\mathbf{r}_i}\dot{\mathbf{x}} = \mathbf{0} \qquad \text{for } i = 1 \text{ or/and } 2. \quad (2)$$

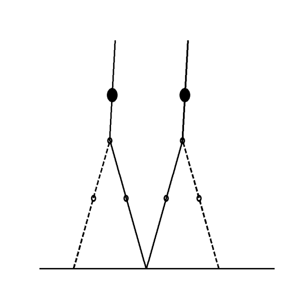
The joint variables θ_i for $i = (1,\ 2,\ 3,\ 4)$ as functions of the generalized coordinates are:

$$\theta_1 = q_2 - q_1, \quad \theta_2 = q_5 - q_2, \quad \theta_3 = q_5 - q_3, \quad \theta_4 = q_3 - q_4. \quad (3)$$

Definition of the ballistic motion

Statement of the problem

- Let $\mathbf{x}(0)$ be an initial configuration $t = 0$.
- Let $\mathbf{x}(T)$ be an final configuration $t = T$.



Definition of the ballistic motion

ballistic motion be in single support: $\Gamma = 0$.

$$\mathbf{A}(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{h}(\mathbf{x}, \dot{\mathbf{x}}) = \begin{bmatrix} \mathbf{D}_1 & \mathbf{D}_2 & \mathbf{D}_3 & \mathbf{D}_4 \end{bmatrix} \begin{bmatrix} \Gamma_1 \\ \mathbf{0}_{3\times 1} \end{bmatrix} + \mathbf{J}_{\mathbf{r_1}}^{\top}\mathbf{r}_1,$$

with the constraint equation for the stance leg tip fixed on the ground:

$$\mathbf{J}_{\mathbf{r_1}}\ddot{\mathbf{x}} + \dot{\mathbf{J}}_{\mathbf{r_1}}\dot{\mathbf{x}} = \mathbf{0},$$

and with the constraint equation for the knee of the stance leg locked in the swing phase:

$$\mathbf{D}_1^{\top}\ddot{\mathbf{x}} = 0.$$

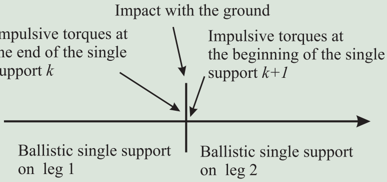
- problem: Which velocity vector $\dot{\mathbf{x}}(0)$ such that $\mathbf{x}(t)$ starting from $\mathbf{x}(0)$ reaches $\mathbf{x}(T)$

$\Rightarrow$ A boundary value problem solved using a Newton method

Impulsive control

decomposition of the impulsive impact.

- After impact the velocity of the biped has to be equal to the founded initial velocity. $\Rightarrow$ impulsive impact.



- Let $\dot{\mathbf{x}}^b$ be the final velocity vector of the current ballistic swing,
- Let $\dot{\mathbf{x}}^a$ be the initial velocity vector of the next ballistic swing.

The structure of the instantaneous double support

First sub-phase: Impulsive phase.

$$\mathbf{A}[\mathbf{x}(T)](\dot{\mathbf{x}}^- - \dot{\mathbf{x}}^b) = \begin{bmatrix}\mathbf{D}_1 & \mathbf{D}_2 & \mathbf{D}_3 & \mathbf{D}_4\end{bmatrix}\begin{bmatrix} I_1^- \\ \mathbf{I}_{3\times 1}^- \end{bmatrix} + \mathbf{J}_{\mathbf{r_1}}^\top \mathbf{I}_{\mathbf{r_1}}^-. \tag{4}$$

$$\mathbf{J}_{\mathbf{r_1}}\dot{\mathbf{x}}^- = \mathbf{0}_{2\times 1} \tag{5}$$

The velocity of the inter-link angle of the stance (hind) leg after first sub-phase remains zero, therefore

$$\mathbf{D}_1^\top \dot{\mathbf{x}}^- = 0. \tag{6}$$

$\mathbf{I}_{3\times 1}^-$ applied by human.

The structure of the instantaneous double support

Second sub-phase: Passive impact.

Knee of the leg 1 is unlocked, knee of the leg 2 is locked with I_4. The *second* sub-phase: passive impact. The stance leg lifts off the ground (Hypothesis).

$$\mathbf{A}\left(\dot{\mathbf{x}}^{+}-\dot{\mathbf{x}}^{-}\right)=\begin{bmatrix}\mathbf{D}_1 & \mathbf{D}_2 & \mathbf{D}_3 & \mathbf{D}_4\end{bmatrix}\begin{bmatrix}\mathbf{0}_{3\times 1}\\ I_4\end{bmatrix}+\mathbf{J}_{r_2}^{\top}\mathbf{I}_{\mathbf{r_2}} \tag{7}$$

The associate equation:

$$\mathbf{J}_{\mathbf{r_2}}\dot{\mathbf{x}}^{+}=\mathbf{0}_{2\times 1} \tag{8}$$

To take into account the locking of the knee of the leg 2, we have to complete equations (7) and (8) with equation:

$$\mathbf{D}_4^{\top}\dot{\mathbf{x}}^{+}=0. \tag{9}$$

The structure of the instantaneous double support

Third sub-phase: Impulsive impact.

$$\mathbf{A}\left(\dot{\mathbf{x}}^{a}-\dot{\mathbf{x}}^{+}\right)=\begin{bmatrix}\mathbf{D}_1 & \mathbf{D}_2 & \mathbf{D}_3 & \mathbf{D}_4\end{bmatrix}\begin{bmatrix}\mathbf{I}^{+}_{3\times 1}\\ I^{+}_{4}\end{bmatrix}+\mathbf{J}^{\top}_{\mathbf{r_2}}\mathbf{I}^{+}_{\mathbf{r_2}} \tag{10}$$

There are 27 scalar equations to find 29 unknown variables, which are the components of the vectors and scalars:

- $\dot{\mathbf{x}}^{-}(7\times 1)$, I^{-}_{1}, $\mathbf{I}^{-}_{3\times 1}(I^{-}_{2},\ I^{-}_{3},\ I^{-}_{4})^{\top}$, $\mathbf{I}^{-}_{\mathbf{r_1}}(2\times 1)$ (for the *first* sub-phase),
- $\dot{\mathbf{x}}^{+}(7\times 1)$, I_4, $\mathbf{I}_{\mathbf{r_2}}(2\times 1)$ (for the *second* sub-phase),
- $\mathbf{I}^{+}_{3\times 1}(I^{+}_{1},\ I^{+}_{2},\ I^{+}_{3})^{\top}$, I^{+}_{4} and $\mathbf{I}^{+}_{\mathbf{r_2}}(2\times 1)$ (for the *third* sub-phase).

Cost functional 1/3

With the impulsive torques, the cost functional is

$$W = \sum_{i=2}^{4} \int_{T-}^{T} \left| \Gamma_i^-(t)\dot{\theta}_i(t) \right| \mathrm{d}t + \sum_{i=1}^{3} \int_{T}^{T+} \left| \Gamma_i^+(t)\dot{\theta}_i(t) \right| \mathrm{d}t$$

$$W = \sum_{i=2}^{4} W_i^- + \sum_{i=1}^{3} W_i^+ \tag{11}$$

Cost functional 2/3

The energy due to the impulsive torques becomes [Formal 82]

$W = \sum_{i=2}^{4} W_i^- + \sum_{i=1}^{3} W_i^+$ with:

Values W_i^- $(i = 2,\ 3,\ 4)$ are calculated as follows:

$$W_i^- = \left| I_i^- \frac{\dot{\theta}_i^b + \dot{\theta}_i^-}{2} \right| \quad \text{if} \quad \dot{\theta}_i^b \dot{\theta}_i^- \geq 0 \quad i = 2, 3, \text{ and } 4,$$

$$W_i^- = \left| I_i^- \frac{(\dot{\theta}_i^b)^2 + (\dot{\theta}_i^-)^2}{2\left[\dot{\theta}_i^- - \dot{\theta}_i^b\right]} \right| \quad \text{if} \quad \dot{\theta}_i^b \dot{\theta}_i^- < 0 \quad i = 2, 3, \text{ and } 4,$$

$$\begin{aligned} &\dot{\theta}_2^b = \dot{q}_5^b - \dot{q}_2^b, \quad \dot{\theta}_3^b = \dot{q}_5^b - \dot{q}_3^b, \quad \dot{\theta}_4^b = \dot{q}_3^b - \dot{q}_4^b, \\ &\dot{\theta}_2^- = \dot{q}_5^- - \dot{q}_2^-, \quad \dot{\theta}_3^- = \dot{q}_5^- - \dot{q}_3^-, \quad \dot{\theta}_4^- = \dot{q}_3^- - \dot{q}_4^- \end{aligned} \tag{12}$$

Cost functional 3/3

The energy due to the impulsive torques becomes [Formal 82]

$W = \sum_{i=2}^{4} W_i^- + \sum_{i=1}^{3} W_i^+$ with:

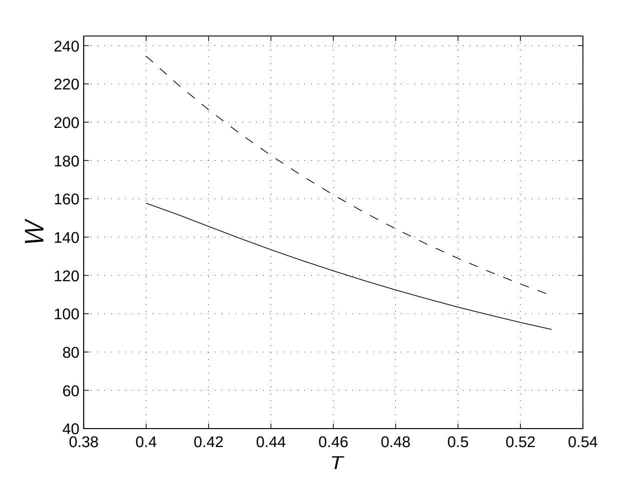
Values W_i^+ $(i = 1,\ 2,\ 3)$ are calculated using analogous formulas:

$$W_i^+ = \left| I_i^+ \frac{\dot{\theta}_i^+ + \dot{\theta}_i^a}{2} \right| \quad \text{if} \quad \dot{\theta}_i^+ \dot{\theta}_i^a \geq 0 \quad i = 1, 2, \text{ and } 3,$$

$$W_i^+ = \left| I_i^+ \frac{(\dot{\theta}_i^+)^2 + (\dot{\theta}_i^a)^2}{2\left[\dot{\theta}_i^a - \dot{\theta}_i^+\right]} \right| \quad \text{if} \quad \dot{\theta}_i^+ \dot{\theta}_i^a < 0 \quad i = 1, 2, \text{ and } 3.$$

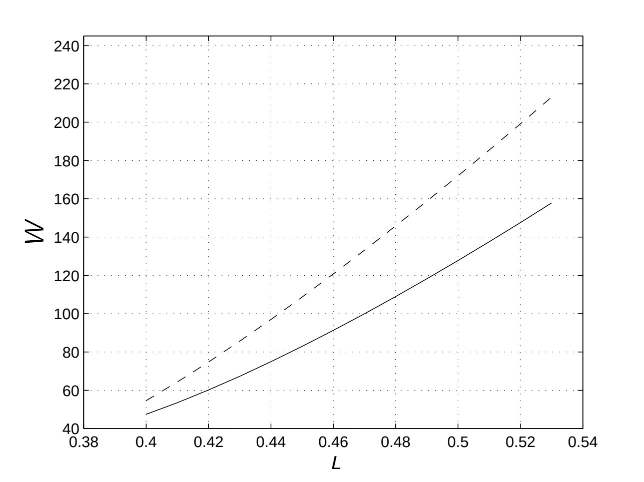
$$\begin{aligned} &\dot{\theta}_1^+ = \dot{q}_2^+ - \dot{q}_1^+, \quad \dot{\theta}_2^+ = \dot{q}_5^+ - \dot{q}_2^+, \quad \dot{\theta}_3^+ = \dot{q}_5^+ - \dot{q}_3^+, \\ &\dot{\theta}_1^a = \dot{q}_2^a - \dot{q}_1^a, \quad \dot{\theta}_2^a = \dot{q}_5^a - \dot{q}_2^a, \quad \dot{\theta}_3^a = \dot{q}_5^a - \dot{q}_3^a \end{aligned} \tag{13}$$

Energy cost as a function of T. (1/2)



For human with the exoskeleton (diamond), and for human alone (circle).

Energy cost as a function of L. (2/2)



For human with the exoskeleton (diamond), and for human alone (circle).

Conclusion and perspectives 1/2

Conclusion

- The planar five-link anthropomorphic bipedal mechanism is considered as a mechanical model of a human walking.
- The links of the exoskeleton are strongly strapped to the corresponding links of the biped.
- A passive exoskeleton without any sources of energy and actuators; the knee of the stance leg of our exoskeleton (and as consequence of the human) is locked using mechanical brake device, but the knee of the swing leg is unlocked.
- It is shown theoretically the efficiency of mentioned above passive exoskeleton for human carrying a load.

Perspectives

- To add feet to our biped.
- to extend to 3D motions.
- To extend this work with optimal walking gaits.