Study and optimisation of a biped equipped with wearable assist device.

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1 Introduction

The musculoskeletal disorders as well as for patients and elderly with mobility impairments are actually social worries. As a consequence during the last few years, several biomechanics studies and realizations of walking assist devices are carried out. For example, Priebe and Kram [1] compare the metabolic power consumption for ten young adults walking without assistance and using two-wheeled, four-wheeled and four-footed walker devices. Zhang and Hashimoto [2] present a trajectory generation method for a robotic suit to assist walking by supporting the hip joints. Ikeuchi *et al* [3] propose a wearable walking assist device. This device, with a seat, two upper frames, two lower frames, and two shoes is disposed along the inner side of the user's legs. It can always maintain the assist force vector in the direction from the center of pressure of floor reaction to the center of mass of the user's body by using two actuators. Despite this great activity the design of a wearable walking assist device with an optimal structure from the point of view of small moving mass and low energetic dispense is still an open problem. Human's walking with an assist device is a very complex orchestration of muscle forces, actuator torques, joint motions, and closed kinematic chains. This paper deals with the problem of the best distribution of torques for a given wearable walking device which assists a seven-link planar biped during a given cyclic walking gait. To get this reference walking gaits, several approaches can be defined. For example the cart-model, or the linear inverted pendulum model, based on the zero moment point ZMP

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can be efficient to design a walking gait; see [4] and [5]. A walking gait based on capture point regulation is developed in [6] or in [7]. The capture point is the location on the ground where a biped needs to step in order to come to a stop. Another approach employed to generate walking patterns for biped robots is based on central pattern generators ($CPGs$) and do not require any physical model of the biped; see [8] and [9]. The reference motion of the biped can be based on record of human motion [10], [11]. In this paper the walking patterns is defined through an optimization algorithm. To study the efficiency of the walking assist device, the torques of the biped without and with the wearable device will be compared. Several levels of assistance will be considered. These levels of assistance are respectively the biped fully assisted, the biped partially assisted in the hips, in the knees and in the ankles respectively.

1.1 Studied biped with its wearable walking assist device

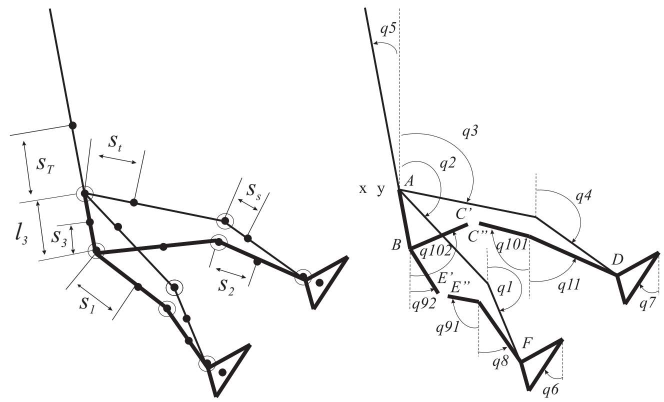
The wearable walking assist device, is composed of a seat, attached to the bottom of the trunk, two upper frames, two lower frames, and two shoes. The wearable device has a similar shape than human with two shins, femurs and shoes. The connection of the wearable walking assist device with human corresponds to the complete feet and to the base of the trunk according to Fig. 1. The physical parameters of the biped are similar to those of a human subject, [12]. The whole mass of the biped is 75 kg, its height is 1.75 m. Table 1 gathers the physical parameters of the biped and the walking assist device. The head mass is included in the trunk that length is l_T.

	Mass (kg)	Length (m)	Inertia ($kg{\cdot}m^2$)	center of mass (m)
Foot and shoe	$m_f = 0.678$	$L_p = 0.207$ $l_p = 0.072$ $H_p = 0.064$	$I^f = 0.012$	$s_{px} = 0.0135$ $s_{py} = 0.0321$
Shin	$m_s = 4.6$	$l_s = 0.497$	$I^s = 0.0521$	$s_s = 0.324$
Thigh	$m_t = 8.6$	$l_t = 0.41$	$I^t = 0.7414$	$s_t = 0.18$
Trunk	$m_T = 16.5$	$l_T = 0.625$	$I^T = 11.3$	$s_T = 0.386$
Seat	$m_3 = 2.0$	$l_3 = 0.1$	$I^T = 0.3$	$s_3 = 0.05$
Upper frame	$m_1 = 3.0$	$l_1 = 0.392$	$I^1 = 0.04$	$s_1 = 0.1127$
Lower link	$m_2 = 2.0$	$l_2 = 0.3645$	$I^2 = 0.02$	$s_2 = 0.169$

Table 1: Physical parameters of the seven-link biped and of the walking assist device.

1.2 Modeling of the biped equipped with a wearable walking assist device

The dynamic model of the biped equipped with the walking assist device is calculated using the equivalent tree structure in which the generalized variables satisfy the constraints of both closed loops and after adding the external forces



(a) (b)

Figure 1: Planar biped with its walking assist device in bold line.

and moments between the cut links as external forces and moments. Through the virtual work principle, these constraints equations can be expressed in the dynamic model by adding terms $\mathbf{J}_i^\top \lambda_i,\ i = 1,\ 2$. Here $\mathbf{J_i}$ is the 3×15 Jacobian matrix and vector $\boldsymbol{\lambda}_i = \mathbf{f}_{c_i}{=}[f_{x_i}, f_{y_i}, m_{z_i}]^\top$ defines the wrench, which is composed of the external forces and moments for each loop closure; see Fig. 1. The generalized vector $\mathbf{x}$ is

$$\mathbf{x} = [q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_8, q_{91}, q_{92}, q_{101}, q_{102}, q_{11}, x, y]^\top.$$

Here x and y are the hip coordinates; see Fig. 1. Angles q_1, q_2, q_3, and q_4 define the absolute orientation of the shin and thigh for both legs. The absolution orientation of the trunk and seat is defined through q_5. Angles q_6 and q_7 describe the absolute orientation of feet. The absolute orientations of the two branches of the upper frames and the lower frames are respectively described with q_8, q_{91}, q_{92}, q_{101}, q_{102}, and q_{11}. The relationships of the biped equipped with the walking assist device can be written as:

$$\mathbf{A}(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{h}(\mathbf{x}, \dot{\mathbf{x}}) = \begin{bmatrix} \mathbf{D} & \mathbf{J}_1^\top & \mathbf{J}_2^\top \end{bmatrix} \begin{bmatrix} \boldsymbol{\Gamma} \\ \mathbf{f}_c \end{bmatrix} + \mathbf{J}_{\mathbf{r}_1}^\top \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{m}_{1_z} \end{bmatrix} + \mathbf{J}_{\mathbf{r}_2}^\top \begin{bmatrix} \mathbf{r}_2 \\ \mathbf{m}_{2_z} \end{bmatrix}, \tag{1}$$

with the constraint equations,

$$\begin{gathered} \mathbf{J}_{\mathbf{r}_i}\ddot{\mathbf{x}} + \dot{\mathbf{J}}_{\mathbf{r}_i}\dot{\mathbf{x}} = \mathbf{0} \text{ for } i = 1 \text{ to } 2, \\ \begin{bmatrix} \mathbf{J}_1 \\ \mathbf{J}_2 \end{bmatrix} \ddot{\mathbf{x}} + \begin{bmatrix} \dot{\mathbf{J}}_1 \\ \dot{\mathbf{J}}_2 \end{bmatrix} \dot{\mathbf{x}} = \mathbf{0}. \end{gathered} \tag{2}$$

$\boldsymbol{\Gamma}$ is the $n_a \times 1$ vector of the applied joint torques, $\begin{bmatrix} \mathbf{r}_i & \mathbf{m}_{i_z} \end{bmatrix}^\top$, with $i = 1$ to 2, are the resultant wrenches of the contact efforts with the ground reaction in both feet, and $\mathbf{f}_c{=}[\mathbf{f}_{c_1}^\top, \mathbf{f}_{c_2}^\top]^\top$. $\mathbf{J}_{r_1}$ and $\mathbf{J}_{r_2}$ are the 3×15 Jacobian matrices for the constraint equations in position and orientation for both feet, respectively. $\mathbf{A}(\mathbf{x})$ is the 15×15 symmetric positive definite inertia matrix, $\mathbf{h}(\mathbf{x}, \dot{\mathbf{x}})$ is the 15×1 vector, which groups the centrifugal, Coriolis effects, and the gravity forces. The torque matrix $\mathbf{D}$ is composed of 0 and 1.

Several distributions of torques are considered for the walking assist device. The number of torques n_a varies from 6 when only the human exerts torques to 12 when human and all the joints of the walking assist device system exert torques. In the single support, with a stance foot and with flat foot contact on the ground the number of degrees of freedom is six.

2 The reference cyclic walking gait

The goal of this study is to compare the energy consumption for a given reference walking gait adopted by the biped alternately without and with its wearable assist device.

In this paper the reference walking gait is computed for the biped without the wearable assist device. This walking gait is cyclic, *i.e.* all steps are identical. Each step is composed of a single support phase and an impact. In single single support the stance foot has a flat contact with the ground. When the swing foot impacts the ground the other foot takes off the ground. The evolution of each joint of the biped is prescribed with a third order polynomial function, of which the coefficients are calculated through a parametric optimization algorithm of the integral of the square of torques for a given walking step length at several velocities; see [13] and [14]. The cyclic walking gait is defined such that the conditions of the flat contact for the stance foot are satisfied, no sliding, no take off and no rotation of this stance foot.

3 Study of the optimal distribution of the torques for the biped with the wearable assist device

The biped equipped of a wearable assist device tracks the walking cyclic gait defined in Sec. 2. The optimal distribution of the torques for the biped and its wearable assist device is studied for the four following cases. Firstly the biped is fully assisted, the wearable assist device provides six torques. The three other cases are defined such as the wearable assist device provides two torques in the hips, in the knees, or in the ankles. For each case, at each sampling time during one step of the cyclic gait, an optimization algorithm is stated. To define this optimization algorithm let us multiply the matrix equation (1) with the matrix $\mathbf{J}^{\perp}(12 \times 15) = [\mathbf{J}_{\mathbf{r}_1}^{\top} \;\; \mathbf{J}_{\mathbf{r}_2}^{\top}]^{\perp}$ to obtain a model without reaction force on the stance foot such that.

$$\mathbf{J}^{\perp}\mathbf{A}(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{J}^{\perp}\mathbf{h}(\mathbf{x}, \dot{\mathbf{x}}) = \mathbf{J}^{\perp}\begin{bmatrix}\mathbf{D} & \mathbf{J}_1^{\top} & \mathbf{J}_2^{\top}\end{bmatrix}\begin{bmatrix}\mathbf{\Gamma} \\ \mathbf{f}_c\end{bmatrix}. \tag{3}$$

The left hand side of (3) is know because it is function of the reference walking gait. The maximal value of the rank of the matrice $\mathbf{J}^{\perp}\begin{bmatrix}\mathbf{D} & \mathbf{J}_1^{\top} & \mathbf{J}_2^{\top}\end{bmatrix}$ is equals to 12. Then when the biped is fully assisted at each sampling time there are $18 - 12 = 6$ variables, among the set of the components of the torques and of the efforts for both loop closures, which can be chosen as optimization variables. When the biped is partially assisted in the hips, the knees or the ankles, at each sampling time there are only $14 - 12 = 2$ optimization variables. Then an optimization algorithm can be stated for the four cases to determine the optimization variables. The considered criteria for $k = 1, \cdots, N = 50$ with $\Delta = T/50$, are:

$$C_{1k} = \mathbf{m}_k^{\top}\mathbf{m}_k, \tag{4}$$

where $\mathbf{m}_k = \mathbf{m}(t = k\Delta)$ is the vector of the torques provided only by the biped, and

$$C_{2k} = \Gamma_k^{\top}\Gamma_k. \tag{5}$$

where $\Gamma_k = \Gamma(t = k\Delta)$ is the vector of the torques provided by the biped and the assist device. Constraints are defined to limit the efforts of each loop closure for biped and its assist advice, to ensure that the vertical component of the ground reaction on the stance foot is positive. Furthermore a constraints of no rotation of the stance foot is taken into account.

4 Results

Distributions of the energy consumption are presented Figs. 2 and 3 for a walking speed 0.65 m/s (2.34 km/h) of the biped, considering respectively with criteria C_{1k} and C_{2k}. The considered cases are: the biped is fully assisted, assisted only in the hips, only in the knees and only in the ankles. The costs are compared to the case of the walking without assistance. In this case the biped is not equipped with the walking assist device. Then the weight of the walking assist device is not taken into account.

If the biped is fully assisted its part of energy consumption is less than the part of its assist device. The costs are compared to the case of the walking without assistance, in this case the weight of the walking assist device is not taken into account.

When the optimization criterion, *i.e* C_{1k}, takes into account of the torques of the biped only, the assist device has to provide a very important part of the energy consumption.

With the criterion, C_{2k} the torques of the biped and of the assist device are included in the criterion, as a consequence, the global cost is similar of that of the biped without assistance. The biped torques are not zero but reduced.

The solution of the assistance in the hips only seems efficient to help the biped in good health, the device at least compensate for its weight, it can also reduce the burden of the human according to the criterion optimized.

The assistance at the knee level or ankle level is not interesting since the torque deliver by the human is not reduced by this kind of assistance.

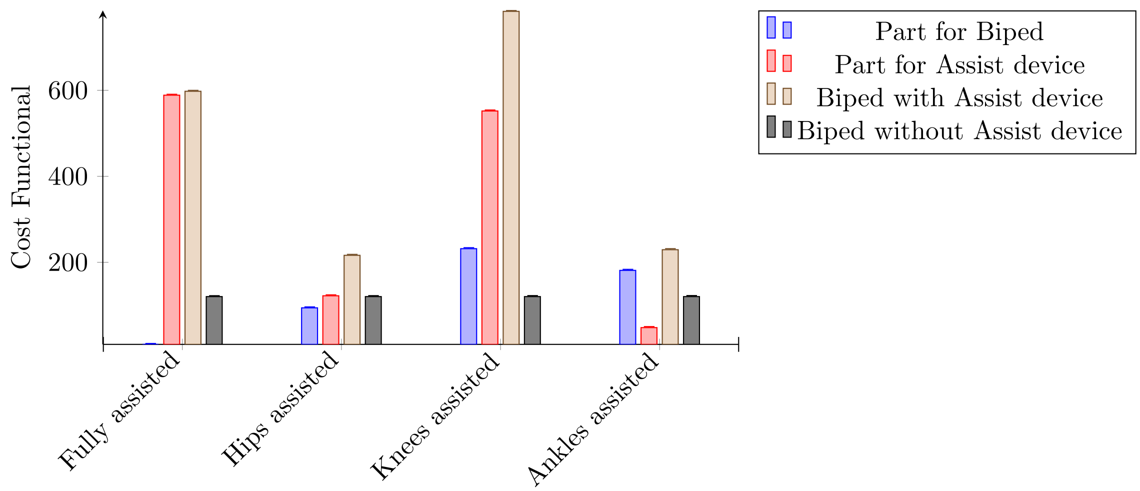


Figure 2: Only the biped torques are minimized: Histogram as a function of different distributions for the torques.

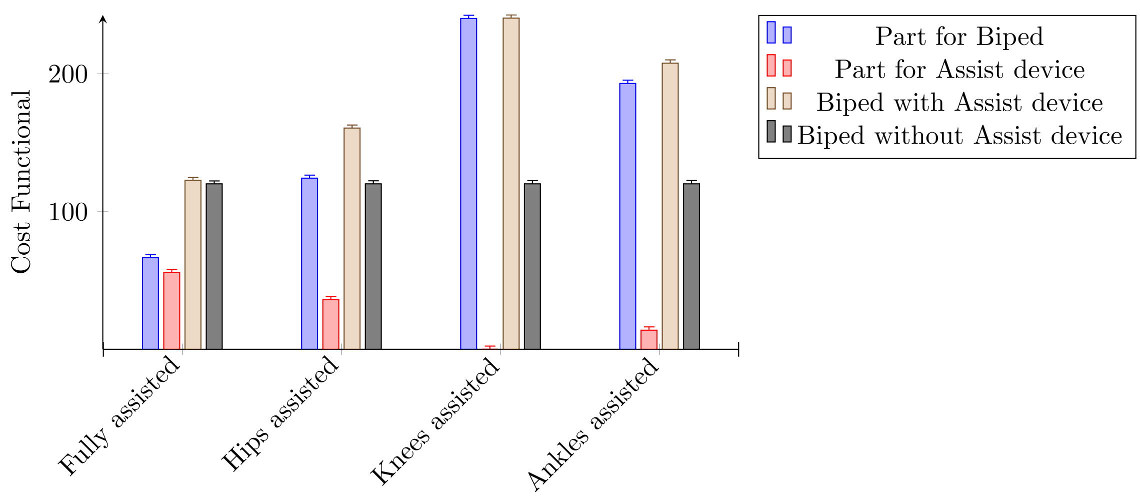


Figure 3: The torques of the biped and walking assist device are minimized: Histogram as a function of different distributions for the torques.

Figures 4(b)-4(d) present the cost as function of the velocity of the biped with and without its assist device. The velocities are between 0.4 m/s and 0.9 m/s (1.44 km/h and 3.24 km/h). Figures 4(a) and 4(b) are relative to the fully assisted biped for C_{1k} and C_{2k} respectively. The energy consumption of the biped fully assisted is smaller than without assistance. With C_{1k} the energy consumption of the assist device is very important. However the torques of the biped are not equal to zero and even increase when the velocity is over 0.6 m/s (2.88 km/h). It is an important drawback for paralyzed human subjects, which is not able to provide any torques. Probably an attention has to be paid on the walking trajectory but also on the design of the assist device to limit this drawback. Figures 4(c) and 4(d) the biped is only assisted in the hips, for C_{1k} and C_{2k} respectively. Figure 4(c), with the assistance in the hips only the part of energy for the biped is less than for the case of the autonomous biped. Figure 4(d), the energy consumptions for both, assisted biped or autonomous biped are very close. These curves confirm that to increase the autonomy of the biped the assistance in the hips only is a good compromise.

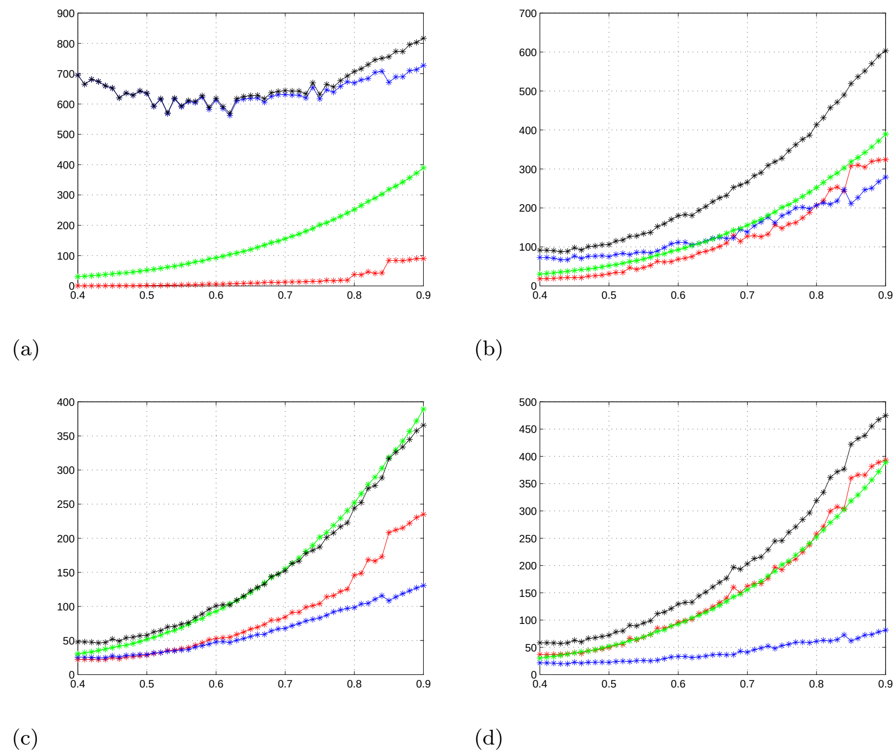


Figure 4: Torque cost as function of the velocities: Biped without assistance (green), Part for Assist device (blue), Part for Biped (red), Addition of the biped and assist device parts (black). (a) fully actuated, criterion C_{1k}; (b) fully actuated, criterion C_{2k}; (c) assistance in the hips only, criterion C_{1k}; (d) assistance in the hips only, criterion C_{2k}

5 Conclusion

The paper have presented the torques cost of walking with several actuations of a walking assist device in the case of simple walk. It have been shown that full actuation of actuation at hip only are two interesting proposals while actuation at the knee or ankle only are ineffective. A study for several velocities confirms it. It is a necessary and good step to start the process of conception of an assist device. The perspective is the study deeper the optimal placement of the actuators by introducing more complexe walking reference gaits.

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