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Improving energy efficiency of bipedal walking using nonlinear compliant mechanisms

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A method to improve the energy efficiency of a bipedal robot by coupling its thighs with compliant smart mechanisms is introduced. The walking gaits are driven by electric motors in its revolute joints, whose reference trajectories are generated via numerical optimization. The optimized nonlinear characteristic of the compliant mechanism modifies the free oscillation frequency of the system that matches the current double step frequency even under different conditions, which results in a very high energy efficiency.

1 Introduction

In recent years, the possibility of using humanoid robots in everyday life has rapidly increased, e.g. robots which support rescue missions in natural disaster scenarios. Developing these robots with a high flexibility requires not only a proper control strategy for stabilizing the movement, but also a way to maximize efficiency which significantly determines their operation duration. According to studies on the efficiency of walking, humanoid robots show poor energy efficiency compared to humans [1]. Thus, the goal of the presented study is to improve the energy efficiency of a bipedal walking robot, by adding compliant smart mechanisms in the form of torsion springs into the mechanical system [2]. Environmental influences, namely different ground inclinations, and different walking speeds are considered. Compliant mechanisms provide nonlinear torque-angle characteristics, which results in a better energy efficiency compared to linear springs from a previous study [3].

2 Method

The planar robot model consists of five rigid body segments, representing one upper body, two thighs and two shanks as depicted in Fig. 1(a). These segments are connected by four rotational joints, in which the driving torques for the motion are produced by electric motors. Both thighs are coupled by a compliant mechanism with nonlinear torque-angle characteristics. The walking gait of the robot at a constant speed v is assumed to be periodic, consisting of continuous single support phases and instantaneous double support phases. In the single support phase, the stance leg remains in contact with the ground while the other leg swings forward without scuffing. In the double support phase, the inelastic collision of the swing leg with the ground is modeled as a discrete mapping. At the same time the former stance leg lifts off. At the end of each step, the role of both legs are switched, which is followed by the next step. A hybrid zero dynamics based controller is used to create and stabilize the joint movements, that are synchronized to their reference trajectories described by gait parameters $\boldsymbol{\alpha}$. The stability of the remaining dynamics—the absolute angle of the controlled system—is determined by its Poincaré map. Considering that the robot model is symmetrical and its walking gaits are periodic, the compliant mechanism in the shape of a full-circle is investigated. Two opposite endpoints of the full-circle are supposed to be firmly attached to both thighs; the rotation of the thighs about the hip joint causes the deformation of the mechanism around its central point. This creates a symmetrical nonlinear torque-angle behavior, which is simulated under the approach of large displacements with Euler-Bernoulli beam theory. Different shapes of the characteristics can be produced by varying geometric parameters $\boldsymbol{M}$ of the full-circle, which are considered as changeable mechanical parameters of the robot. Other mechanical parameters, like the total body mass m of 12 kg and the total body height of 1.15 m, are assumed to be constants that only depend on the manufacturing process.

Thus, the robot's energy efficiency is determined by the gait parameters $\boldsymbol{\alpha}$ as well as the mechanical design parameters $\boldsymbol{M}$, which are simultaneously optimized. The cost of transport—the total input energy in the electric motors divided by the mass m and traveled distance ℓ—is the objective of the optimization, that will be minimized. $20\,\%$ of the electrical energy, generated by the electric motor while it is decelerating the movement, is assumed to be recycled for recharging the battery. This assumption guarantees a unique solution of the optimization, in case that the gravity becomes the dominating energy source for walking, instead of consuming electrical energy. Physical conditions while walking on an inclined flat ground are enforced by a number of equality and inequality constraints. In order to explore the maximum potential of improving energy efficiency by coupling the robot's thighs, the optimization process is performed for each condition, combined from different velocities $\boldsymbol{V} = [0.2, 0.3, ..., 1.4]$ m/s and ground inclinations $\boldsymbol{\beta} = [-10^\circ, -9^\circ, ..., 10^\circ]$.

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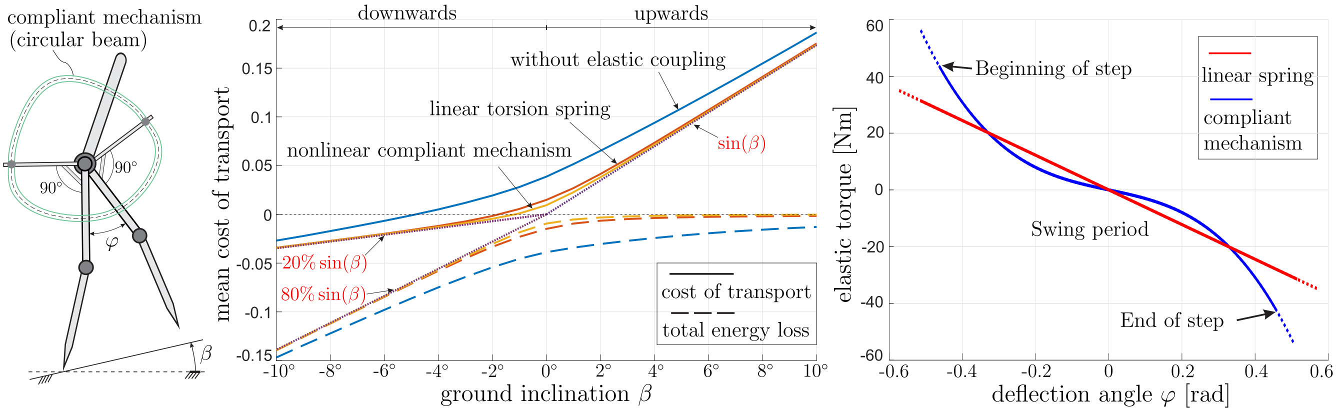
3 Results

The results of nonlinear mechanisms are compared to the previous research in [3], which focused on improving the efficiency by coupling thighs using optimum linear torsion springs. Since the periodic walking gaits are limit cycles of the controlled system, the system's mean energy is constant. It contains energy losses, the kinetic energy and the potential energy of gravity and the compliant mechanism. The gravitational energy is regarded as the lower physical limit of the cost of transport: $20\,\%\sin(\beta)$ for $\beta < 0°$ and $\sin(\beta)$ for $\beta \geq 0°$. Energy losses are normalized by mass m and travel distance ℓ (similar to the cost of transport) and introduced as negative values in Fig. 1(b). The diagram also shows that negative slop angles lead to more energy losses. As the energy supply due to gravity increases, the motors are mainly used to decelerate the movement (generator mode), so that the robot can maintain a constant average velocity. During this process, at least $80\,\%$ of the generated energy turns into heat losses. Another kind of energy losses considered in this study is caused by the collision of the swing leg to the ground, which always occurs at the end of one step. For the purpose of reducing the impact losses, the robot with optimized gaits tries to slow down the movement right before touching the ground. From observing the characteristic in Fig. 1(c), one notices that the optimum compliant mechanism tends to be activated only at the beginning and the end of one step, where the suddenly increased elastic torque assists in decelerating the movement. In the meantime, kinetic energy is stored into the full-circle mechanism as potential energy, which is reused for accelerating at the beginning of next step. During the swing period in the middle of one step, the spring remains inactivated, i.e. the natural dynamics of the swing leg is less suppressed. Similar behaviors were also discovered in the human muscles [4], while human are capable of utilizing their natural dynamics to save energy.

Using nonlinear mechanisms also changes system's natural dynamics. As a result of the optimization, the free oscillation frequency of the swing leg matches with the current double step frequency of walking. The robot is thus able to walk in its resonance even at different scenarios, which means in a very high energy efficiency overall. In this manner, adding optimized nonlinear compliant mechanisms into the robot achieves much more improvements of the energy efficiency, compared to a linear torsion spring, for all studied scenarios. In future works, the nonlinearity of compliant mechanisms will be further investigated, with the aim of developing one single nonlinear mechanism that is suitable in many different environments.



(a) (b) (c)

Fig. 1: (a): Five link robot model with a deformed compliant mechanism attached to its thighs. (b): Mean cost of transport and normalized energy losses. (c): Optimized spring characteristics for $v = 1.4$ m/s and $\beta = 10°$ (solid lines: active operating ranges of the spring).

4 Conclusions

The presented study shows the potential of improving energy efficiency of a bipedal robot by coupling its segments with a full-circle compliant mechanism, which acts like a torsion spring with nonlinear characteristics. The walking gaits and geometric parameters of the mechanism are simultaneously optimized for many different walking scenarios. For all of the studied conditions, the robot is able to walk in its resonance with a very high energy efficiency.

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