

# Inertial lever as a mechanical principle of human walking

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## Summary

The principle of human walking is a fundamental concept in biomechanics to explain the apparent easiness of the normal human walking in terms of the logic of the movement and its mechanical insight concluding what is the reason of the high energy efficiency. It is done so by transferring this knowledge to future biped designs conquering new application domains, including space robotics. Despite the substantial research done in biomechanics the present concepts do not translate well to robotics where not the observation but the re-creation of the human like walking is required. Common hallmark of the present principles is the reduction of the robot mechanism (or in case of human, the body) to a single point mass expecting that simple treatable control algorithms can handle the problem. Then the control actions are acting upon the point mass externally, to represent the locomotion strategy of the whole mechanism after further distribution of control signals to the joint actuators. This approach however doesn't allow to reckon with the internal dynamic interaction of the mechanism neither on practical or conceptual level. Therefore we establish a two-link model as a dynamic counterpart of a theoretical simple machine, called inertial lever, and propose a new principle which originates the forward progression of the mechanism from the internal dynamical interplay of that mechanism. The model is analyzed and the results show that the locomotion effect can be attributed to a discrete regime set by the geometric and dynamical parameters of the walker. The utility of designing a biped control based on that concept is that it takes control strategy to one level up using linear/angular momentum and impulses as control variables avoiding the eventual position control of actuators, allowing to design a biped mechanism with direct drive actuators, and allowing the mechanism to evolve along its natural dynamics to be energy efficient and using future artificial muscle recently under development for space robotics. As a whole a light, agile human like biped with human like walking would be achievable.

## Introduction

While the walking machine operation is based on a pre-established technical principle of walking, the human walking principle is still debated. There is now a tendency to transfer the human walking principle to the machine design and control, to produce speedier, dexterous and energy efficient bipeds (cf. W-Prize). The driving forces are the human-like dexterous design which is lighter and safer in the human environment and its control is simpler and more robust. Artificial muscles are currently under research at NASA for application on humanoids in human habitats in space.

The walking principle itself is not a control algorithm and is not equations of motion and is not a generic dynamic behavior. We use it as a necessary central element to explain why the normal human walking is efficient and elegantly easy for the person. We argue that it centers on a dynamic phenomenon in specific dynamic state of the walker.

## Methods

First we introduce the notion of *inertial lever*. The inertial lever is an extension of the lever of the first kind operating in a dynamic regime. Both levers execute object transfer function based on active forces, but the inertial lever's essential features are the inertial parameters of the linkage and the transfer functionality which is aimed to the lever itself. It can just work in dynamic regime, without actuation it collapses. The inertial lever concept is a rotational analog of the simple static lever, applicable to two-link segmented linkage (having masses) rotated around joints.

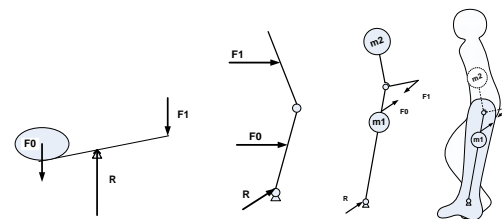


Fig. 1. Lever of first kind and the inertial lever

As a consequence of the force arrangement, the forces mimic the action of the muscle contraction between the trunk and the leg, and the structure is

rotating around both the supporting pivot and the joint in the middle. Then the inertial lever is used as a model human walker. The principle of walking is then sought in the dynamic interaction of the upper and the lower links in 2D. The control algorithm then can be designed on that principle, which remains one, but the major determinant component among the other control design considerations.

**Results**

For exploring the solution of the model's equations of motion, Fig.3, the induced accelerations are plotted as a function of the muscle contraction force

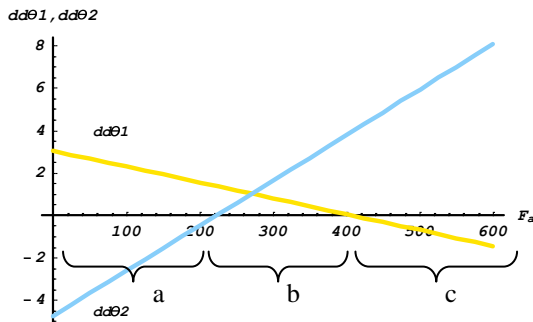


Fig. 2. Instantaneous angular acceleration for links 1, and 2, .

The linkage behavior will depend on the magnitude of the contraction force. It collapses in place, falls backward or keeps vertical configuration according to the zone of the force brackets (a, b, c). Perhaps the surprising effect is that despite two unsuccessful actions its exaggeration results the desired dynamic behavior. This is the phenomenon where the inertial lever manifests itself. It has a discrete zone of validity described by all the geometric and dynamic parameters. Linearity of the graph signifies a principle which expressible in simple form once understood and extendable for a complex mechanism.

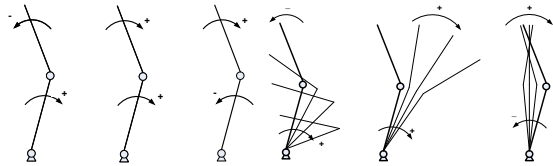


Fig.3. Instantaneous angular accelerations for links 1 and 2, in the three sectors of the action magnitude for the abstracted walking configuration (Fig. 1) and their unfolding synergy of motion phase portrait.

A morphological biped prototype with human dynamic parameters was built using linear electric direct drive motors, with no gears (Jakubik, 2012), and the inertial lever principle has been simulated

coupled with the ankle and swing leg actions for a single step (Fig. 4).

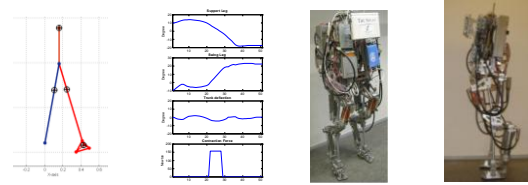


Fig.4. The biped configuration and joint trajectories of the trunk, support & swing legs due to hip impulse

**Discussion**

We proposed a new principle of human walking, introducing the inertial lever model, which postulates the forward processing motion as a result of the interplay of the internal dynamics of the structure. The link segments accelerating to opposite directions, have been also known to the Biomechanics scholars (Zajac, 2002), but further studies in this direction have not been pursued: cf. “The exact nature of that segmental interaction remains elusive, ... It would be unwise to speculate too much on the muscular origin of that transfer.” (Knudson, 2007). The control concept can be formulated in vector entities rather than nonlinear optimization problem yielding position trajectories for the actuators. This allows to deploy a flexible control strategy for each situation, admissible to e.g. neuromechanics approach, rather than to handle it with a trajectory optimization algorithm. The applied forces can be exerted by direct drive motors which are back-drivable allowing the biped's natural motion to be evolved. Most straightforward conjecture is that the ankle push off forces is just a preparatory factor for bringing the body into the dynamic state where the forward propelling inertial lever can regulate the speed of the walker. Therefore the two actions are complementary, better explaining the efficiency of the human walking.

**References**

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