

# Involuntary morphosis - modular simulation of limb damage in quadrupeds

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## 1 Introduction

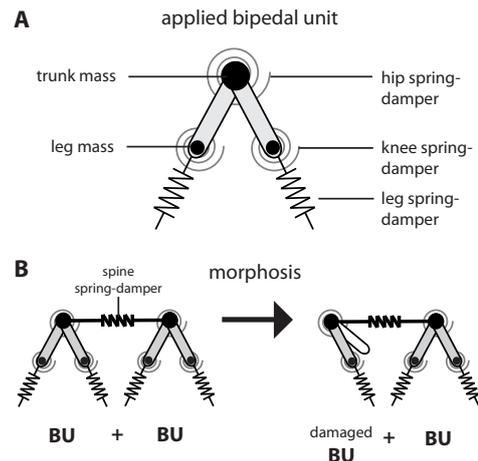
The ability of humans and animals to adjust posture (voluntary morphosis) increases the versatility of locomotion. It allows a better adaptation to a changing environment. Humans, for example, use bipedalism routinely for efficient and fast locomotion. When they enter rough terrain, get older or carry heavy loads, they may use a walking stick to enhance stability and distribute load. From equally interest is functional and postural adaptation to an unintended structural modification (involuntary morphosis) as caused for instance by limb damage. While humans usually use crutches to restore walking ability, quadrupeds can still locomote with only three operative legs at hand. Applying morphosis strategies in robotics could greatly enhance the adaptability of a legged vehicle: An autonomous robot that can morph could cope with limb damage (e.g. during extraterrestrial missions) and could adapt gait and body morphology to different environments.

To investigate how limb damage affects locomotor ability, we introduce the concept of the bipedal unit (BU). The BU consists of a trunk segment with two attached legs. The simulation model of a BU is based on biologically inspired locomotion templates like the spring-loaded inverted pendulum (SLIP) describing the individual leg function. By combining BUs, quadrupeds and multiple-legged systems can be easily described. This kind of modularity is inspired from robotics as a well-established concept to simplify robot design and to understand robot behavior. However, the BU concept is only one singular realization of modularity in computer simulation and could be considered as a first step towards a sophisticated construction kit for simulating and designing legged robots.

In our presentation, we focus on the question how morphosis in a quadruped can be used to cope with limb damage in order to restore the ability for walking or running.

## 2 State of the art

The concept of modularity was successfully applied to different legged robots, e.g. Odin [17], RoomBots [16] and salamander robot [7, 8]. Especially the salamander robot can be regarded as a direct inspiration for our BU concept due to its clear decomposition into modules along the fore-aft axis. While these robots do not need any external stabilization,



**Figure 1:** The bipedal unit concept - one realization of modularity in computer simulation. **A.** Our bipedal unit extends the SLIP template by adding leg mass. **B.** Two bipedal units form one quadruped. A hind limb damage causes gait morphosis: Control and morphology is considered for adjustment.

other systems apply lateral, fore-aft or trunk stabilization. This can be achieved, for instance, with a boom mechanism as realized in the GARP robot [15] and JenaWalkerII [14].

The dynamics of human and animal running (e.g. center-of-mass dynamics) are commonly described with simplified models such as the spring-loaded inverted pendulum (SLIP) model [2, 9, 4]. Forward-dynamic simulations of the SLIP model exhibit stable running patterns without the need for actuation (inherent mechanical stability: [3, 6, 11, 13]). This remarkable feature makes the SLIP model a suitable candidate for a running template [5]. By anchoring the SLIP model in more realistic models, the simulation could provide engineers with design requirements as predicted by the model. Thus, robots could be developed that could benefit from inherent stability which relies on energy-efficiency and dynamic stability.

## 3 Methods

In a simulation study, we adjust leg parameters (e.g. leg and hip stiffness) to compensate for a sudden failure of a quadrupeds hind limb. To assemble the quadrupedal model

we simply connect two BUs with a compliant spine simulated as a prismatic spring-damper element (Fig. 1B). We model the BU in comprising two telescopic springy legs attached to a trunk mass via frictionless hip joints (Fig. 1A). The telescopic leg consists of a leg mass with a linear massless spring underneath. Further, the model has a hip and knee rotational spring-damper element (a linear spring in parallel to a viscous damper). We use actuation of the hip to refill energy that is lost due to leg impact. Hip actuation is achieved by changing the rest position of the hip spring. In fact, our applied BU is an extension of the SLIP model by adding leg masses. With this, dynamic effects of leg rotation (e.g. leg moment of inertia) on running stability can be addressed and torque requirements as well as actuation policies can be investigated in preparation of the robot design. To identify hip actuation policies and model parameters that produce stable running patterns, we use one separate BU and focus on its stability domain. Furthermore, we apply leg retraction strategies [13, 10] to enhance robustness.

#### 4 Discussion outline

To support engineers in robot design, we aim to map the robot together with its environment to a mechanical simulation model. We expect that an iterative, bidirectional transfer between model and robot is beneficial and could yield both models that are modular and robots that are dynamically stable. Within this framework, here, we focused on morphosis strategies that can cope with hind limb damage of a quadruped.

- Which alternative compliant quadrupedal models could be promising?

*Our potential solution:* We try to transfer the SLIP as close as possible. This strategy can guide you through high-dimensional parameter and may break the curse of dimensionality [1].

- Which concepts beside *bio-inspiration* could support the construction of dynamically stable legged robots?

*Our potential solution:* Using robotic-inspiration for model design could accelerate the bidirectional iteration towards a sophisticated match of model and robot. By identifying underlying structures of this model-robot match, a better understanding of human and animal locomotion would be possible. On the other hand, it would support the development of new design concepts for robots.

- Which additional features beside leg mass could be most important for a sophisticated model-robot match?

*Our potential solution:* Adding friction could be beneficial as it was also implemented in the clock-torqued SLIP (CT-SLIP). Robot and CT-SLIP data were in good agreement [12].

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