Bipedal Running: Bioinspired Fundamentals for versatile Humanoid Robot Locomotion

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***Abstract*— The field of humanoid robots has grown in recent years with several companies and research laboratories developing new humanoid systems. However, the number of running robots did not noticeably rise. Despite the need for fast locomotion to quickly serve given tasks, which require traversing complex terrain by running and jumping over obstacles. To provide an overview of the design of humanoid robots with bioinspired mechanisms, this paper introduces the fundamental functions of the human running gait. The paper surveys multiple concepts, i.e. to protect the system against impacts, store kinetic energy at touchdown, use natural dynamics, and transfer energy between joints through couplings. The understanding of the fundamental functions can support engineers to design versatile humanoid robots, without sacrificing versatility against capability.**

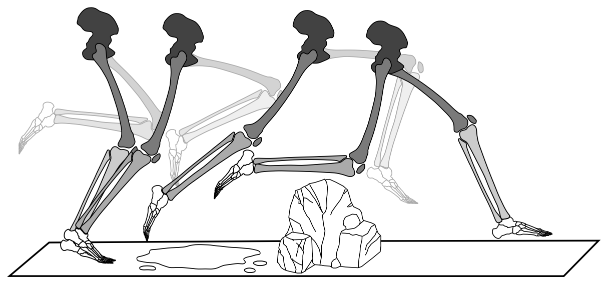

Fig. 1. Running over obstacles with a pronounced knee flexion

I. Introduction

A key objective for humanoid robots is to assist humans at work and replace them in operating dangerous situations. These robots need to be able to change their locations to fulfill their respective tasks. This includes traversing complex terrain with obstacles (see Fig. 1). While humans would simply run to their urgent tasks, most humanoid robots are solely able to walk. Only some robots like Asimo (Honda, Tokio, Japan), Atlas (Boston Dynamics, Massachusetts, USA), and Cassie (Agility Robotics, Oregon, USA) demonstrated their ability to run at considerably faster speeds than walking [1]–[3].However, as stated by Tajima et al. in 2009 [4], it is still true that human running outperforms bipedal robot running. Except for Atlas and Cassie, the shown obstacles in Fig. 1, would place an impossible task for robots with very high step frequencies and short double floating times like Asimo. Therefore using bioinspired mechanisms and functions from succeeding bipedal species is a valid starting point to better understand and enhance the current state-of-the-art running robots.

The research about bioinspired mechanisms is mainly conducted by observing animal behavior and then analyzing their e.g. kinematics or anatomy to extract principles and mechanisms like closed kinematic chains or oblique axes which offer new mechanisms for the field of humanoid robots [5], [6]. These studies have inspired leg designs like the Bird Bot or others [7], [8]. Cursorial species (adapted to running), like ostriches, are good role models for the pure running gait, but they are highly optimized and lack versatility [9].
For versatile locomotion, humans are better role models, as they are ambulatory mammals (adapted to walking) that offer the full range of bipedal gaits and a large support polygon for upper body tasks which are necessary for robots to manipulate the environment.

The bipedal locomotion of humans can be split into two general modes of progression: 1) walking, which is characterized by an out-off-phase energy flow from kinetic to potential energy with a rocker kinematic [10]. The concept uses inherited natural dynamics of the system (e.g. motions due to inertia or impulse conservation) to minimize the metabolic cost of the human [11].; and 2) running, which is very similar to the gait of cursorial species. It bases on an exchange of kinetic and potential spring energy due to the elastic properties of the musculoskeletal system [11].

Due to the small amount of running humanoid robots, it seems not straightforward how the bioinspired running concept can be transferred to humanoid technology. Therefore, the main contribution of this paper is the review of the fundamentals of the human running gait and a design guideline for the mechanical and control strategy of humanoid robots. It aims to offer the reader a conceptual understanding of fundamentals and mechanisms for achieving a running gait. The paper begins with a short introduction of the running gait in Sec. II. Afterward, the paper follows the depicted functions in Fig. 2. Each section introduces the general phenomena and the bioinspired solutions before stating robotic concepts to achieve the fundamental functions. Sec. III summarizes the functions in a design guideline before the paper concludes with an outlook on future research.

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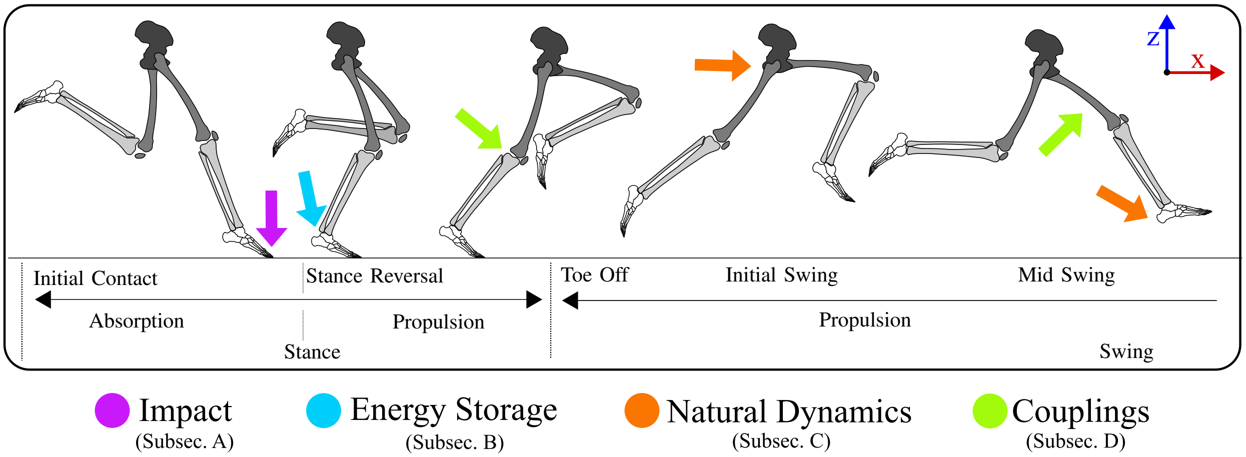


Fig. 2. Fundamental functions of bipedal running. The arrows represent instances in which the function is active. The gait cycle is not drawn to scale.

II. Bioinspiration and Robotic Concept in Running Gait

In general, humans use three main types of gaits for locomotion: walking, running, and sprint running. The gait transitions from walking to running at rising speeds. This results in changes in the ground reaction forces and the duty factor (ratio between stance and swing time) due to the shift of the introduced progression mode [11]–[13]. Fig. 2 introduces the locomotion type of running which uses the same fundamental functions as sprinting. The two gaits solely differ in parameters like speed, swing times, or a different foot posture [11], [12], [14]. This paper focuses on the sagittal plane of the locomotor unit (lower body). However, the functions of the other planes and the upper body should not be neglected in the humanoid design, as it also contributes to the energy efficiency and balance with concepts like the spinal-engine theory [15]. The arrows in Fig. 2 depict the active fundamental functions for achieving a running gait. It is helpful to reopen the figure at the beginning of each section to associate the function to the instance in the gait cycle.

A. Impact

Impacts can be described as the physical event of a collision between two bodies. At collision, the ground exerts a force to break the runner's motion. The force shocks (impulse) mainly occur along the vertical (z) and horizontal (x) axes resulting from the vertical foot velocity v_{foot} and gravity g [16]. While impacts in the x-direction can be reduced through swing leg retraction (see Subsec. II-C), vertical impact forces F_z are present in running and primarily determined by the unsprung mass's M_{eff} momentum as follows

$$\int_0^T F_z(t)dt = M_{\text{eff}}(-v_{\text{foot}} + gT), \qquad (1)$$

where T is the duration of the impact [16].

Unsprung mass: The general concept of the unsprung mass is illustrated in Fig. 3a. Sketch (I) shows the desired spring-mass characteristic, ignoring the spring- and foot mass. Adding an unsprung foot mass M_{eff} in (II) results in a force shock that propagates through the system. Further adding a spring k_{ground} in (III) results in a reduced impact but unstable contact. Solely a viscoelastic contact in (IV) enables a traceable and feasible solution for robotic systems. Additionally to the unsprung mass which directly collides with the ground, a fraction of the mass above adds to the unsprung mass as well. The concept can be explained by the alpha factor which is defined in [18] for a linear case. The alpha factor in the rotational case explains the fraction of the ground reaction force (GRF) which is orthogonal to the rotational motion of the ankle joint. As an example, the whole leg mass needs to be considered as M_{eff}, when landing with straight knees (kinematic singularity), as the GRF passes straight through the joint centers.

1) Bioinspiration:
Fig. 3b shows the vertical GRF of a human running with three different foot postures. While rearfoot strikers (RS) have two force peaks, a forefoot striker (FS) has solely one peak. The slope of the GRF at impact is called loading rate (LR) which stresses the human tissue [16]. An estimate for the duration T and vertical force F_z of an impact in human running is 50ms and $1.5 - 3$ times the body weight [16]. The authors in [19] showed, that the trailing peak of RS can be explained by a two-mass model. The first peak of the GRF can be modeled with the lower bodies (below the knee) impact and the second peak pertains to the residual bodies response. The forefoot case in Fig. 3b has one additional degree of freedom (DOF) α due to fewer contact constraints. This shifts the lower body GRF peak inside the upper body GRF peak. A midfoot striker (MS), who after initial contact flattens its heel, uses the same mechanism to delay the first peak until the heel strikes. As shown in Fig. 3b and concluded from [16], the loading rate can be reduced by changing the running foot posture. The negative side effect of a forefoot posture is the increased ankle torque, due to the lever arm to the center of pressure Δ_{COP} throughout a gait cycle.

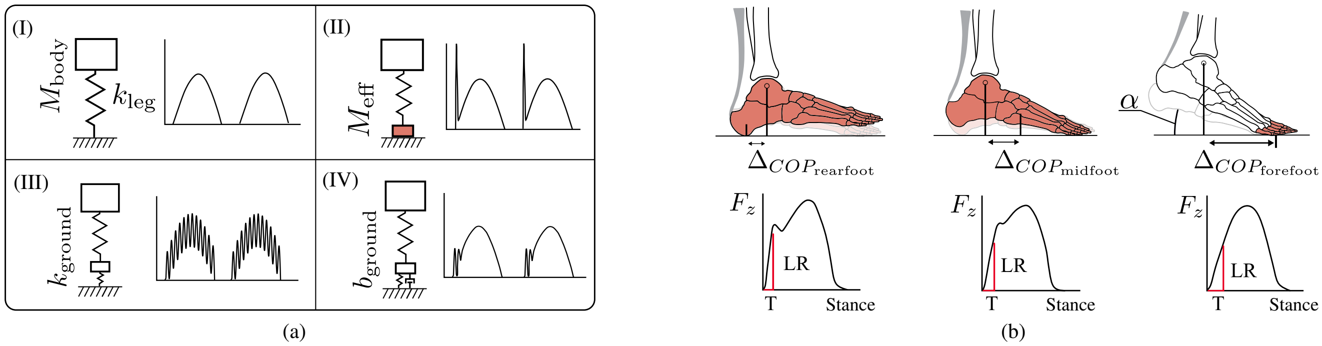


Fig. 3. (a) Modeled contact force of a body mass M_{body} and effective mass M_{eff} with elastic and viscoelastic components (insp. by [17]) (b) Three different foot postures at strike (bold), post strike (grayed out) with their vertical ground reaction force (F_z) and loading rate (LR) (insp. by [16])

Additionally, nature has evolved various methods to cushion against the high impacts. Especially plantigrade (flat-footed) species have numerous DOFs in their foot. They all contribute to shock absorption with interconnected small muscles, ligaments, and fascia [20]. Furthermore, biology uses fat bubbles as shock absorbers in the heel and ball of the foot [20], [21]. Authors in [17] examined their viscoelastic properties and their ability to decrease the loading rate on the system.

2) Robotic Concepts:
The subject of impacts is prominent within the robotics community. While most current robots are designed to avoid impacts, they are unavoidable and prominent in a running style. One main problem of the impact or associated unsprung mass is the risk of breaking the actuator components. At impact, the shock propagates through the system and bearings in the form of an angular velocity change of the joints. Once it arrives at the gearbox of the actuator, the effective inertia I_{eff} can be given as

$$I_{\mathrm{eff}} = I_{\mathrm{link}} + N^2 I_{\mathrm{motor}}, \tag{2}$$

which consists of the link inertia I_{link} and the reflected-inertia of the motor $N^2 I_{\mathrm{motor}}$ counteracts the rotational velocity change. The reflection is due to the gearing ratio N, which scales the motor inertia I_{motor}. To not exceed the maximum gearbox load it is important to minimize N, due to its quadratic influence [18]. In [22], the authors created a reflected inertia matrix to determine the resulting inertia of all contributing factors for their foot.

The research in the field of impact-aware robotics resulted in the development of series elastic actuators (SEA) [23] or proprioceptive actuators (PRA) [22] as used in the MIT Cheetah to survive the impact. While SEA are using elastic components within the actuator, the concept of PRA requires a high-torque motor and low-inertia leg to be actively compliant.

Most humanoid robots are using viscoelastic dampers below the foot to reduce the impact before it reaches the actuators. The authors in [24] conducted experiments with several materials with an optimization result appearing to be close to the characteristics of a human foot.

3) Design Considerations:
In running, the unsprung mass of the system collides repetitively with the ground. This impact can be reduced by changing to a forefoot posture but is not canceled out completely. Most robots are using damping elements at their feet to reduce the force shock to the system. The residual force shock is propagated to the actuator which should use PRA or SEA to protect the actuator components. Control concepts using a spring-mass model inspired inverse dynamic control should be aware that tracking imperfections at impact can occur due to the residual unsprung mass. The primary running goal of absorbing the impact and recoiling the energy during the generation phase should be considered when designing dampers and springs.

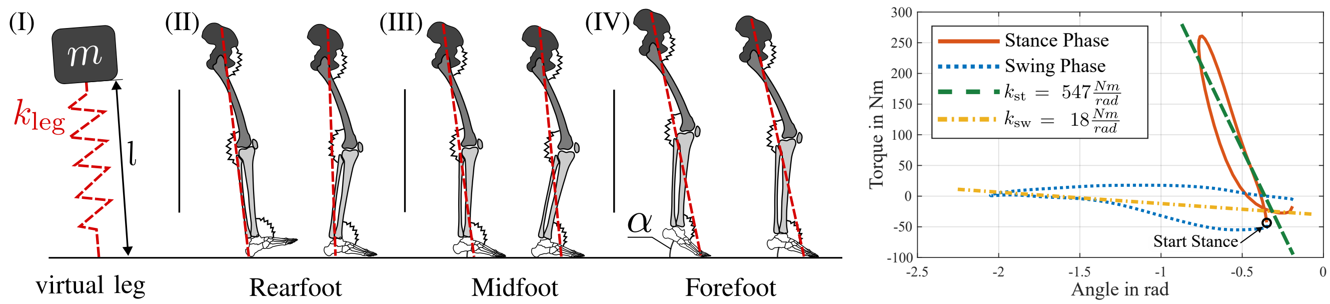
B. Energy Storage

The second bioinspired function shown in Fig. 2 is based on the physical characteristics of springs which introduces the ability to store energy $E_{\mathrm{pot.spring}}$. In contrast to walking, the potential and kinetic energy in running is in phase, which shows that passive vaulting mechanisms as used in walking are limited [11], [13]. Storing the present kinetic energy is thus a very useful mechanism to increase the efficiency of a running locomotor system [25]. Therefore, the spring-mass model, shown in Fig. 4a (I), is a widely used model for running [26]. The amount of stored potential energy, given as

$$E_{\mathrm{pot.spring}} = \frac{1}{2} k \Delta l^2, \tag{3}$$

depends on the spring constant of the virtual leg k, which is termed stiffness, and on the square of the spring displacement Δl.

1) Bioinspiration:
Each of the lower body's sagittal plane joints are inheriting viscoelastic properties from the connected muscle-tendon units (MTU). Several MTUs are connected to each joint in an antagonistic fashion (on both sides). Their elastic elements resist angular changes in the joint (stiffness). By coactivation, antagonistic MTUs increase their stiffness, which changes the total joint stiffness, as they are pulling on each other. This is used in several species to tune the system's stiffness



(a) (b)

Fig. 4. (a) (I) Spring-mass model with the virtual leg spring and three running leg postures with their initial contact (left) and post contact (right) pose (b) Knee angle - torque (stiffness) plot of a forefoot runner at $3.5\mathrm{m/s}$ with the stance phase stiffness k_{st} and swing phase stiffness k_{sw}; data from [27]

TABLE I
HUMAN STIFFNESS VALUES[1] & CONTRIBUTED LEG POWER[2]

	Stiffness			Contributed Power	
Ankle	$327-1175$	$\frac{\mathrm{Nm}}{\mathrm{rad}}$	[31]	42%	[32]
Knee	$390-1094$	$\frac{\mathrm{Nm}}{\mathrm{rad}}$	[31]	19%	[32]
Hip	$124-151$	$\frac{\mathrm{Nm}}{\mathrm{rad}}$	[27]	39%	[32]
Leg	$25-35$	$\frac{\mathrm{kN}}{\mathrm{m}}$	[31]	100%	[32]

[1] at $2.6-6.5\mathrm{m/s}$ in stance phase for [31] and $2.5-4.5\mathrm{m/s}$ in gait phase for [27]
[2] at $3.25\mathrm{m/s}$

to a certain eigenfrequency, which enables highly efficient locomotion [28], [29].

The requirements of a running gait on the stiffness of the system are very divalent, as the ankle- and knee joint stiffness is highest in the stance phase and nearly slack in the swing phase (see Fig. 4b). Tab. I presents the reported range of mean stiffness values in the literature of human running with speeds from $2.6-6.5\mathrm{m/s}$. A detailed analysis can also be found in [30].

To increase the running speed, one option is raising the leg stiffness, to achieve a shorter stance phase. The knee is seen as the key component for adapting the leg stiffness for velocities up to $6.5\mathrm{m/s}$ [31]. The ability to adjust the stiffness (variable stiffness) is one of the key advantages of a biological system to achieve the energy-efficient characteristic in running. This also enables the divalent knee and ankle stiffness in the stance- and swing phase. Therefore, the linearization of a stance and swing phase stiffness is a simplification as the human constantly adapts its stiffness (quasi-stiffness).

Tab. I also reports the main contributors to the total average positive leg power done by a human at 3.25 m/s. It shows the ankles small lead in power contribution of 3% over the hip. With faster speeds however, the hip becomes the leading contributor due to higher swing phase demands [11], [32]. The authors in [33] report a rough estimate for the energy efficiency of the ankle (positive to negative work) of approximately 63% in running at 3.8 m/s, ignoring viscous- and other losses as well as proximal contributions (see Subsec. II-D) [34].

One reason for the large power contribution of the ankle in slower running speeds is the "ankle catapult" for RS, which makes use of the large upper body mass loading the achilles tendon in the stance phase before releasing the energy in form of a fast foot acceleration due to the comparably small foot mass [35], [36]. Further studies highlight the arch of the foot, which mainly stores the energy in a parallel spring (plantar fascia) and contributes to the total leg work by 8.6% at 2.7 m/s and 17% at 4.5 m/s [37], [38]. This contribution is part of the ankle power in Tab. I.

Leg Posture: Beside being an important factor for reducing the impact, the foot and leg posture also define the contribution of each joint stiffness to the overall leg stiffness k_{leg}. The rolling motion of a RS in Fig. 4a (I) relies on a higher ankle stiffness [39]. The spring motion of a FS in Fig. 4a (II) has a higher knee stiffness [39].
Based on the posture in Fig. 4a, a FS has an additional remaining DOF α as the rotational contact constraint is free. A FS is thus able to displace the virtual leg Δl by lowering the ankle, without necessarily changing the leg posture at the hip and knee joint. In the case of a MS and RS, a change in l results in an overall leg posture change, due to coupled joint positions. The redundancy of the FS can be validated by the pose dependent jacobian $\mathbf{J}$, which determines the virtual leg spring k_{leg} based on the joint stiffness matrix $\mathbf{K}_{\mathrm{joints}}$:

$$k_{\mathrm{leg}} = \mathbf{J}^T \mathbf{K}_{\mathrm{joints}} \mathbf{J}. \tag{4}$$

The additional DOF of a FS can be used to change the leg configuration and thus leg stiffness or decouple the hip motion while still following the spring-mass modeled center of mass (COM) trajectory in running.

2) Robotic Concepts:
Energy storage is not popular in humanoid robotics and is rather a side field. Most robots do not incorporate any kind of mechanical storage and are rather rigid systems with some activities in active compliant systems in which the controller creates a virtual spring behavior. The general ideas of elastic locomotion started with a series of legged robots from Raiberts Lab in the 1980s [40]. The 3D One-Leg Hopper achieved a dynamic motion without using a spring model [41]. In 2016, the ATRIAS team designed their robot

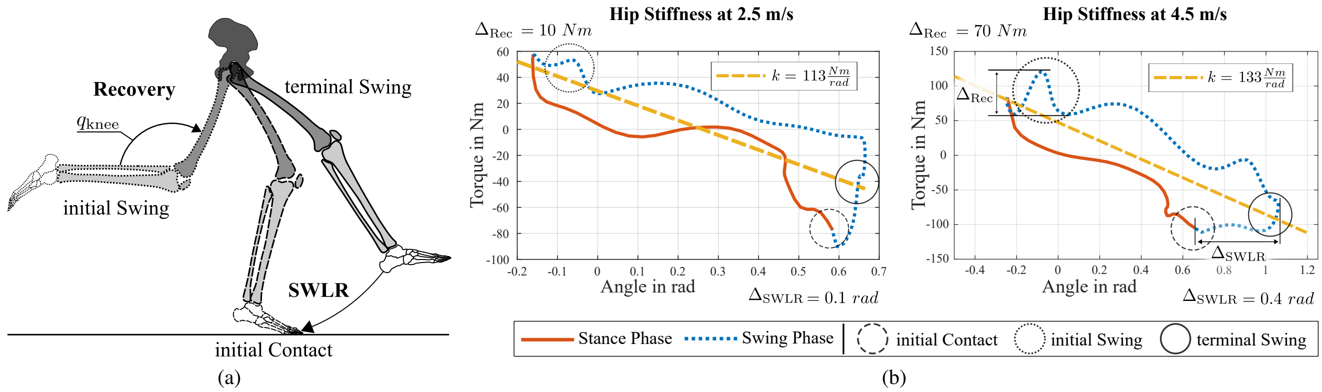


Fig. 5. (a) Three leg postures depicting the recovery and swing leg retraction (SWLR) mechanism; (b) Hip stiffness at 2.5 and 4.5m/s with the recovery torque Δ_{Rec} and SWLR angle Δ_{SWLR} of forefoot runner 18 from [27]

to comply with the spring-mass template model aiming for efficient locomotion, which afterward was the inspiration for Cassie [42], [43]. Krupp concluded that designing a robot for the highest speed, and thus highest stiffness degrades the efficiency and controllability of the system [18].

The nearby field of compliant actuators is constantly working on the accompanied control challenges within humanoids with fixed or variable stiffness like the DLR-David [44]. The control architecture of humanoid robots is often split into two systems. The rigid body controller computes a desired torque for the joint space, and the low-level torque controller sets the motor current to the actuator. In this concept, the rigid body controller is typically unaware of the current spring state. As a result, the rigid-body controller does not use the springs as an energy reservoir.

3) Design Considerations:

The introduction of springs can reduce the power demand of the system, as large parts of the stored energy are recoiled in the generation phase. According to the literature, variable knee stiffness mainly drives leg stiffness in running. Fixed joint stiffness in the knee and ankle cause problems in the swing phase as they are hindering the natural dynamics of the system (see Subsec. II-C). Variable stiffness actuators can be a game changer for enabling faster energy return at various running speeds. Forefoot running decouples the virtual leg spring length from the hip position, as the leg posture has an additional DOF. Elasticity increases the complexity of the control framework, however, to use the energy storage capacities elastic elements are needed and thus also an energy-aware rigid body controller.

C. Natural Dynamics

The third bioinspired function is based on the natural dynamics of a pendulum relying on gravity and inertia. It is depicted in the swing phase of Fig. 2 introducing the oscillating hip. The idea that the natural dynamics of the leg generate a passive pendulum-like swing motion for walking was already stated in 1836 [45].

1) Bioinspiration:

To enable the larger range of motion in the hip at higher running speeds with similar swing time durations [12], humans reduce their leg inertia (see Recovery). The introduced hip stiffness in Tab. I changes minimally within individuals at speeds of $2.5 - 4.5$ m/s (see Fig. 5b) and thus is only a small contributor to the speed adaptation [27]. This is valid in slower speeds, as in higher speeds above 5.5m/s the stride dynamics changes to rather adapt the stride frequency than the step length [12].

Fig. 5 shows the stiffness plot at 2.5 and 4.5m/s. Observing the angle-torque trajectory, two main mechanisms (Δ_{Rec} and Δ_{SWLR}) can be found, which deviate from the otherwise spring-like trajectory. The bioinspired mechanisms are called recovery and swing leg retraction, which will be detailed in the following sections.

Recovery: The recovery action of the swing leg occurs in between the terminal stance and initial swing phase and contributes to the overall mechanism of reducing the swing leg inertia. The recovery mechanism can be found in Fig. 5 with Δ_{Rec} showing a rapid hip acceleration shortly after push-off. The rapid acceleration results in a knee flexion q_{knee}, shown in Fig. 5a, due to the lower leg inertia [46]. The average knee angle q_{knee} rises with running speed from $90°$ in running to $105°$ in sprinting [11].

Combined with couplings (see Subsec. II-D) and muscle work, the knee further flexes and reduces the leg length and thus the leg inertia within the swing phase [29]. Due to the reduced inertia, the swing leg is able to achieve a higher angular velocity. Fig. 5b shows that the maximum torque Δ_{Rec} needed to accelerate the leg increases with higher speed from 10 to 70 Nm. The rise of Δ_{Rec} is used to further increase the knee angle, which consecutively reduces the total power demand due to the decreased swing leg inertia.

Swing Leg Retraction: Fig. 5a shows the swing leg retraction (SWLR) mechanism starting in the terminal swing phase and ending in the late swing phase, after the foot reaches its maximum distance from the body it retracts before touching the ground. This mechanism is also called velocity matching [14]. The main effect is the reduction of the horizontal GRF, by matching the horizontal ground speed. However, it is not the goal to diminish the external forces, but rather to find an optimum for the force production needed to propulse the body forward and upwards. Fig. 5 shows the increase of Δ_{SWLR} with speed, from 5° to 25° ($0.1-0.4\mathrm{rad}$). The mechanism and its effect on the stance time, as well as the leg stiffness, was already introduced in several papers [47], [48].

2) Robotic Concepts:
Mochon and McMahon were one of the first to explain the swing leg trajectory in a robotic context [49]. Based on these findings Raibert and McGeer developed the first systems using the systems natural dynamics [13], [40]. The pendulum motion requires a leg design with rather high inertia and low reflected motor inertia, as otherwise, the motor inertia hinders the natural dynamics of the swing leg (compare Eq. 2).
Reducing the swing leg inertia is prominent within the robotics community and is mostly applied by couplings forcing the foot towards the body [7]. The authors are unaware of robots using rapid hip acceleration to use the natural dynamics of the lower leg for knee flexion initiation. In [50], the authors analyzed the effect of SWLR on their planar running robot Phides with results favoring the solution for future developments as it improved stability and reduced touchdown forces and impact energy loss.

3) Design Considerations:
A rigid-body controller should be aware of the natural dynamics in its system and relax its control effort to e.g. use the lower leg inertia for knee flexion after push-off. This allows to increase the efficiency through passive motions, which are occurring by shaping the robot's design, e.g. the leg inertia [13]. The recovery and SWLR mechanisms help the system to be more energy efficient by reducing the leg inertia for the swing motion and the horizontal GRF. In both instances, biarticular couplings are assisting the motion, which is detailed in the following section.

D. Couplings

The fourth mechanism in Fig. 2 introduces couplings. Couplings constrain the position of one DOF with one or more other DOFs. Fig. 6 (I) shows a parallel closed linkage four-bar mechanism (pantograph) with a hard coupling resulting in a fixed coupling ratio of the knee angle q_1 to the ankle angle q_2. Coupling (II) is soft, as the coupling between q_1 and q_2 depends on the variable stiffness element k_1. Other elements like linear actuators or dampers, can change the coupling ratio depending on the current position or velocity.

1) Bioinspiration:
The concept of couplings is often used in the field of biotensegrity to explain several biological structures like fish mouths and horse muscles [51]. It bases on closed kinematic chains, e.g. passive linkages like four-bar mechanisms or biarticular muscles [51], [52]). While passive linkages are based on bones or ligaments, biarticulation (BI) is based on isometric-activated muscles spanning over two joints (shown in Fig. 6). This results in the contribution of the biarticular muscles on two joints as shown in Tab. II.

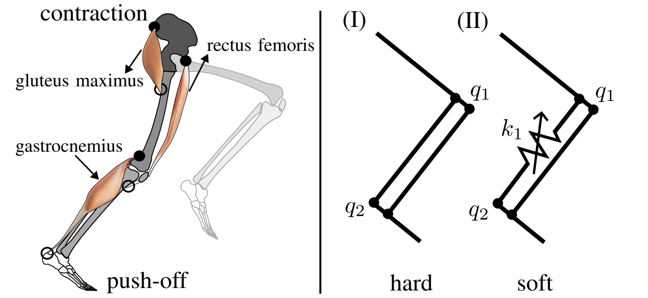


Fig. 6. Isolated view on the biarticular mechanism at push-off; filled circle: muscle origin, transparent circle: muscle insertion; hard (I) and soft (II) coupling with variable stiffness

TABLE II
BIARTICULAR COUPLING AT PUSH-OFF[1]

	Gastroc.	Rect. Fem.	Gluteus max.	Torque
Hip	-	Flex.	Ext.	0
Knee	Flex.	Ext.	-	0
Ankle	Plan.flex.	-	-	Plan.flex.

[1] in a fictional torque equilibirum position; Abbreviations for: plantar-, flexion, extension and the introduced muscles in Fig. 6

Fig. 6 introduces the mechanism of BI in a fictional equilibrium position at push-off. The accompanying Tab. II presents the participating BI muscles: rectus femoris (RF) and gastrocnemius (GN) with the resulting joint torque after activation of the monoarticular gluteus maximus (GM). Due to the isometric contraction of the RF and GN, the GM activation results in an ankle push-off from the ground. Due to this characteristic, the BI muscles are described as "energy straps", as they transfer energy from proximal to distal joints [11].

The unexpected resulting joint motions created the "lombard paradoxon" [53], [54]. Kuo elaborated on the paradoxon in detail and highlighted that the origin and insertion, respectively, their distance to the joint defines the system's dynamics [54].

Couplings enable the contribution of proximal muscles to the distal joint work for push-off impact absorption [11]. The hamstrings (BI muscles) also initiate the SWLR motion in Subsec. II-C. Other instances of BI can be found in [11]. The biological system can tune the coupling ratio by coactivation of the muscles (see Subsec. II-B) to change the corresponding stiffness and thus coupling ratio (see Fig. 6 (II)).

2) Robotic Concepts: The Chebyshev linkage, a four-bar mechanism, resulted in one of the first walking mechanisms in 1894 [55]. The topic of passive linkages evolved and Burgess [56] recently summarized present and newly found linkages suitable for bioinspired designs. The author concludes four main advantages with a proximal actuator position, an optimal mechanical advantage, a high level of integration, and power amplification. These advantages are, e.g. valid for the Bird Bot, which was inspired by the fast-running style of emus and ostriches and used their coupling and clutching concepts for planar running [7]. The Bird Bot has a fixed spring in its four-bar linkage, which makes the coupling force dependent. Other systems could make use of clutches, elastic elements, or linear actuators to tune the coupling ratio based on, the element's characteristic. The authors in [57] recently reviewed the topic and summarized the applications in robotic devices.

3) Design Considerations:
Coupling mechanisms are widely used in many robotic systems to, e.g. resolve high power demands. The main advantages are the proximal positioning and the shared load of the actuators. Couplings need to be chosen with care, as coupled actuators can increase the total output in one leg posture, but increase the geometric work (actuators working against each other) in another leg posture. Using soft or active couplings is advantageous. Generally, couplings are very helpful for increasing the system's capabilities and assisting the fundamental functions but need to be well designed to not reduce the overall versatility.

III. Design Guidelines

The paper surveyed the fundamental principles of the human running gait. The first function covered the necessity to protect the system against the impact at touchdown. The unsprung mass, which yields the impact of the system, can be reduced by using a forefoot ground contact. The propagating impact through the system, which jeopardizes the gearbox, can be further reduced with viscoelastic dampers in the foot. The actuator design should be designed to have a low gearing ratio or series elastic component to reduce the reflected motor inertia. The impact might be reduced, however, at touchdown the GRF might still have a peak at higher running speeds, which should be considered when using an inverse dynamics control approach based on the spring-mass model.
Consecutive to the impact, the second function, which introduces the energy storage and elastic components of the system, is active. The present kinetic energy at touchdown should be accumulated in elastic elements to reduce the requirements of the actuators at push-off. It is important, that the rigid-body controller is aware of the spring state, to use it as an energy reservoir. The spring-mass model is often used to describe the system's dynamics with a virtual leg spring. A forefoot contact enables a redundant system by having fewer contact constraints, which can be used to adjust the virtual leg stiffness or decouple the hip from the leg posture. While the hip can be modeled as a constant spring, the characteristic of the ankle and knee is very divalent. In the stance phase, the joint stiffness is high, while nearly slack in the swing phase. This yields the mechanism of variable stiffness to achieve energy-efficient human running.
Low joint stiffness is important to achieve the third fundamental function of natural dynamics in running gait. While running, not only the center of mass is exchanging potential and kinetic energy, also the segments are constantly conserving their energy. The control concept can use the inertia of the lower body to initiate a knee flexion in the initial swing phase by a rapid hip acceleration. A flexed knee reduces the inertia of the swing leg which consecutively increases the angular velocity. The inertia of a system is thus a design parameter, which should comply with the desired locomotion.
The first three fundamentals are assisted by couplings, which introduce the fourth function. Humans use couplings to transfer energy from one joint to another. At touchdown, proximal muscles are absorbing energy, and at push-off injecting energy into the ankle. This is achieved by biarticular muscles, which span over two joints creating a four-bar linkage in the system. The system can benefit from couplings, as the maximum output can be increased by sharing the load between the actuators.
Designing a system based on these fundamental functions enables versatile humanoid locomotion. The system can still use passive mechanisms in walking and balancing with a large support polygon for upper body manipulations. Furthermore, the system can run with impacts and high propulsive forces at push-off with the stored energy and transfer of energy with coupled joints. The natural dynamics of the system enable an energy-efficient foot clearance to pass higher obstacles on the ground.

IV. Conclusion

With the aim to enable versatile and dynamic locomotion in humanoid robots, this paper introduced four fundamental functions of human running to serve as guidelines for improved robot design: 1) impact mitigation, 2) energy storage, 3) natural dynamics, and 4) couplings. For each fundamental function, the bioinspired concept is explained and the corresponding robotic concepts are discussed with recommendations for future implementations. The introduced bioinspired fundamentals are a first step towards a general review of bioinspired mechanisms in bipedal species, which could benefit the community in multiple aspects, i.e. by reducing the research effort of design engineers for bipedal robots. Considering the mentioned fundamentals in a robot design could drastically improve the capabilities and versatility of future humanoids.

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