Running and Walking with Compliant Legs

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It has long been the dream to build robots which could walk and run with ease. To date, the stance phase of walking robots has been characterized by the use of either straight, rigid legs, as is the case of passive walkers, or by the use of articulated, kinematically-driven legs. In contrast, the design of most hopping or running robots is based on compliant legs which exhibit quite natural behavior during locomotion.

Here we ask to what extent spring-like leg behavior could be useful in unifying locomotion models for walking and running. In so doing, we combine biomechanical experimental and computer simulation approaches with theoretical considerations and simple legged robots.

We have found that (1) walking and running result from mechanical stability which corresponds to the experimentally observed gait dynamics, (2) running is a subset of stable movement patterns for high system energies, and (3) walking with knee flexion during stance can result from passive leg mechanics with elastic structures spanning the joints.

1 Introduction

What are the common design and control principles of legged locomotion?

On the one hand, we must consider the internal leg function: the number of leg segments, the arrangements of muscles, ligaments and other soft tissue within the leg and the appropriate muscle activation patterns in order to generate a desired leg behavior.

On the other hand, we need to integrate the leg into an encompassing control system – the global leg function – such that we can observe a “complete” movement pattern including legs and the supported body. This means that if we have simple, biologically meaningful models describing the leg behavior

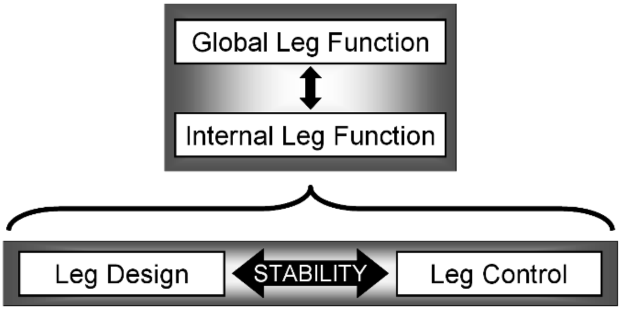

Fig. 1. Leg function is divided into global and internal leg functions. Global leg function describes the leg control based on a given internal leg function. The internal leg function addresses issues of design and control of a segmented leg itself. To identify control strategies we analyze the mechanical stability of selected leg designs at different levels of leg function

in a desired movement task, we can use these leg templates (i.e. simplified models, [7]) to derive the required leg control strategy.

A very simple description of the leg behavior is provided by the spring-mass model. Here, the force generated by the leg during the stance phase is assumed to be proportional to the amount of leg compression, i.e. the more the leg shortens the larger the corresponding leg force. Despite its simplicity this model is a very powerful tool to predict movement strategies or jumping performance [22]. It can help to better understand the role of leg segmentation or muscle function during fast movements. Furthermore, spring-like leg operation seems to ease required control action even in highly dynamic situations with reduced sensory perception.

In legged locomotion we observe a sudden change in leg behavior between walking and running. This gait transition occurs in most animals at about the same dimensionless speed at Froude number equal to approximately 0.4, which is calculated using the equation v^2/gl (where v is the forward speed, g is the gravitational acceleration, and l is the leg length, [14, 26, 8, 18]).

This suggests the possibility that common, underlying mechanical principles may exist for legged systems. If this is true, mechanical design methodologies could be derived which would yield systems equally capable of walking and running gaits, depending on the selected system condition (e.g. system energy) or movement strategy.

In order to change gait, either the mechanical system could change its behavior in an internal and self-organized fashion or the overlaying control strategy could initiate the gait transition. This might point to distinct movement primitives (i.e. programs) which could be used to select gaits. In order to control a given mechanical system we could apply simple feedback control approaches (e.g. a PD controller). In this paper we rather suggest a different approach. First, we build simplified mechanical models either on a computer (i.e. simulation models) or as physical models (i.e. robots) and explore their behavior for a variety of reasonable initial conditions and model parameters. Second, we compare the predictions of different proposed models with experiments of human or animal locomotion. Finally, we investigate the influence of the model parameters on the movement performance and try to estimate the best control strategy in order to improve system stability with the lowest possible sensory effort.

In this paper we describe a series of simple models of internal and global leg functions and compare them with the behavior of two experimental legged robots. We will start with two models addressing internal leg behavior, a three-segment model with elastic joints and a two-segment model with an extensor muscle. Afterwards, we present models describing the global leg function in spring-mass running and walking. Finally, we explore the behavior of the simple legged robots, imitating walking and running.

2 Internal Segmentation of the Leg

In order to operate in a spring-like fashion, a segmented leg must be able to compress and extend stably. With two segments, a leg would have no problem doing so as long as the internal leg joint is operating in a spring-like fashion as well. Leg compression directly translates into joint flexion, which in turn results in higher joint torque and consequently, in increased leg force. The only problem could be in the generation of linear leg spring behavior as observed in human and animal locomotion. Therefore, the joint spring should be nonlinear in terms of the torque-angle characteristics, i.e. being more compliant at low compressions and being stiffer at larger joint flexion.

If we extend the two-segment leg by one segment we obtain a three-segment leg similar to the human leg, with foot, shank and thigh. Now, leg compression can result in different outcomes. Let us assume both internal leg joints (e.g. ankle and knee) to be equally stiff and let us further assume completely symmetric leg geometry (equal segment lengths, equal initial joint angles). We would then expect a transformation of leg compression into equal flexion of the two joints. Interestingly, however, this is not the case (Fig. 2).

In the three segment leg, stability requires a local minimum of the mechanical system energy with respect to variations in the joint angle configuration (ankle and knee) and a given leg length (e.g. distance hip to toe). At a certain amount of leg compression however, this local minimum in system energy changes into a local maximum when loading both joints equally. Consequently, symmetric bending of both joints becomes unstable. Even perfect adjustment of the joint springs cannot prevent asymmetric joint behavior if a certain critical amount of leg compression is exceeded [25]. Here, one leg joint starts to extend whereas the second joint flexes rapidly. As a consequence, the leg force is not shared equally between the joints and the leg stiffness drops. This situation would lead to high local stresses at the flexing joint which could

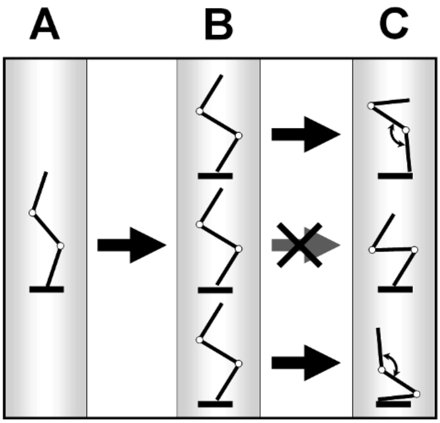

Fig. 2. Three-segment model with equal segment lengths (L1=L2=L3) and two joint springs of equal stiffness and equal static equilibrium angles (**A**). After a certain amount of leg compression (**B**) symmetric bending of both joints becomes unstable. Depending on infinitely small perturbations the two joints proceed by rotating asymmetrically, with one extending and the other flexing (**C**)

result in structural damage or failure in a real leg. To avoid this disastrous behavior, different measures can be introduced. One strategy is to steer the leg joint movements by a kinematic control approach, whereby the joint angle is constrained along a desired trajectory. This intervention may work at low energies through the use of a high-bandwidth controller to counteract the system dynamics. At faster leg movements however, a more systematic modification is required. Stability analysis of the three-segment leg reveals that different solutions exist to avoid this intrinsic instability (Fig. 3).

Strategy A: The joint spring characteristics are slightly non-linear, e.g. the joint stiffness increases with joint flexion. If one joint flexes more than the other, the increased joint stiffness compensates for the mechanical disadvantage caused by the joint's increased flexion. The model predicts a higher nonlinearity in joints whose configuration at static equilibrium is characterized by greater extension (e.g. knee compared to ankle). This prediction is confirmed by experimental results. The required nonlinearity of the joint torque characteristics might be provided by the nonlinear stress-strain characteristics of tendons and aponeuroses connecting the muscle to the skeleton as found in human running or jumping [13, 21].

Strategy B: The leg segmentation is asymmetric, i.e. the outer leg segments are different in length. The model predicts that stable leg operation can be achieved if the joint adjacent to the shorter outer segment (e.g. ankle in humans) is more flexed compared to the other leg joint. This finding is in agreement with human leg design.

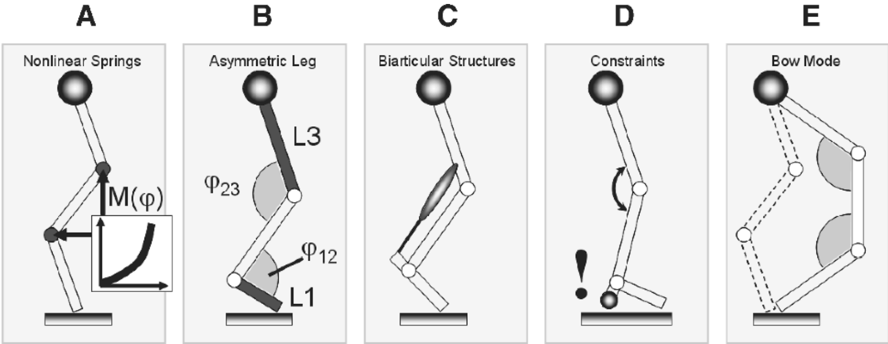

Fig. 3. Five strategies to avoid instability in an elastic three-segment leg: (**A**) nonlinear joint springs, (**B**) asymmetric leg segmentation and leg joint configuration, (**C**) biarticular elastic structures, (**D**) joint constraints, e.g. heel contact, and (**E**) operation in a bow configuration

Strategy C: The risk of out-of-phase joint function due to mechanical instability can be reduced by adding biarticular elastic structures. In the case of asymmetric leg segmentation (Strategy B) it is sufficient to have only one biarticular spring which flexes the more extended joint (knee) and extends the more flexed joint (ankle). The risk of over-extension of the ankle joint is largely avoided by the flexed ankle configuration (about 80–120 degrees) during human locomotion. A biarticular antagonist of the m.gastrocnemius is not required and does not exist in nature.

Strategy D: Even if all previous strategies (A–C) fail to prevent unstable leg operation, there is still another hard-built safety measure to avoid overextension of the more extended leg joint (the knee): the mechanical constraint of joint flexion due to a skeletal structure, e.g. the calcaneus with the heel pad. If the activity of the plantar flexors is not sufficient the heel strike prevents overextension of the knee which would have serious consequences in many athletic movements like running or long jumping.

Strategy E: Finally, there is a strategy to achieve stable leg operation by using a very different nominal leg configuration by swapping the leg joints (from a zigzag or Z-configuration) to the same side with respect to the leg axis (bow or C-configuration). The leg configuration is safe and simple to control at cost of reduced limb stiffness and reduced leg force. It can be found in the upper limbs of humans or in spiders.

All of these strategies guarantee parallel joint operation in a three segment leg and can be found in nature. It is important to realize that these measures are not exclusive and are often implemented in a highly redundant fashion. Similar to the air bags in our cars, the leg includes several design and control strategies to avoid mechanical instability potentially leading to serious damages of the musculo-skeletal system. Elastic joint behavior in itself does not guarantee stable leg operation during contact. However, for the identified leg design and control strategies (Fig. 3) the control of the highly nonlinear segmented leg could be simplified. The results demonstrate that spring-like leg operation can be a key for better understanding the architecture and function of biological legs. On the joint level, spring-like behavior (joint stiffness and nominal angle) can be adapted based on neuromuscular mechanisms [6], [10]. In turn, if all required measures are undertaken to guarantee stable leg operation, spring-like leg operation can result at various loading conditions.

3 Generation of Muscle Activity

Periodic movement patterns as observed in legged locomotion require a cyclic action of the muscles within the body. The time series of the corresponding muscle activation pattern could be the result of different mechanisms. One possibility is direct control of muscle activation by supraspinal commands. In this case the exact timing of all muscles would require a high processing (i.e. high-bandwidth) capacity in the brain. A different approach would be the generation of periodic movement patterns in rhythm generators located in the spinal cord (central pattern generators, [12]). Then the higher control could be reduced to coordinate these pattern generators. Another possibility is the generation of the required muscle activation based on the dynamics of the musculo-skeletal system and sensory feedback to the spinal cord [27]. Such a control strategy could further relax the neural control effort and could take advantage of positive side-effects of the muscle-reflex dynamics. In a simulation study [10], we asked which proprioceptive reflex loop would be capable of generating the required muscle stimulation *STIM(t)* for steady state hopping in place (Fig. 4). Leg geometry is reduced to two massless leg segments with one Hill-type extensor muscle spanning the leg joint. The body is represented by a point mass on top of the upper segment (Fig. 4). Muscle stimulation is assumed to be the sum of a given central command, *STIM0*, and a potential reflex contribution (amplified and time delayed sensory signal based on muscle length, muscle velocity or muscle force).

We found that steady state hopping is possible (1) with an optimized stimulation pattern *STIM0(t)* or (2) based on a constant *STIM0* and positive length or positive force feedback. The predicted maximum hopping height employing positive force feedback is 83% of that calculated using an optimal muscle stimulation pattern and turned out to be robust with respect to simulated external perturbations (e.g. changed ground properties, Fig. 4C). At moderate hopping heights, an almost spring-like leg operation is predicted (Fig. 4B). The simulation results indicate that the generation of the extensor muscle activity in hopping or running tasks could be facilitated by positive force feedback. Instead of giving the muscle a precisely timed activation pattern, the task is now executed based on a constant stimulation (*STIM0)* and proper integration of proprioceptive signals into the activation of the extensor-motoneuron. The control effort is therefore largely reduced and the

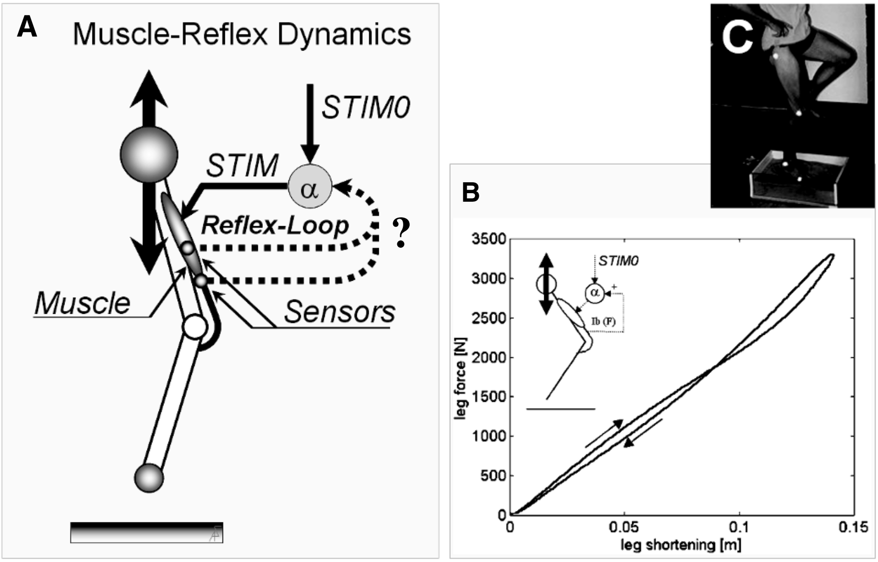

Fig. 4. (**A**) Two-segment leg model with one extensor muscle and proprioceptive feedback. The activity of the α-motoneuron driving the extensor muscle (*STIM*) is assumed to be the sum of a central command (*STIM0*) and a contribution of the reflex loop based on different sensory signals (muscle length, muscle velocity or muscle force). Muscle stimulation signals *STIM(t)* with and without sensory feedback for stable hopping in place are calculated. (**B**) The best hopping performance based on sensory feedback is achieved with positive force feedback and a constant bias signal *STIM0*. Here, spring-like leg behavior is found. (**C**) The muscle-reflex dynamics are robust with respect to environmental changes like hopping on a dissipative substrate (sand)

leg behavior is more robust with respect to perturbations. Furthermore, even with little or no passive compliance (as would be provided by tendons, for instance) the muscle-reflex dynamics produced spring-like leg behavior. In that respect leg stiffness is an emergent steady-state behavior in cyclic hopping (or running) based on the neural integration of sensory information and will therefore adapt to environmental changes detected by the sensory organs.

In the previous sections two simplified models for the internal leg function are introduced. Both models give new insights into how spring-like legs could be designed and controlled. It turned out that compliant leg operation is not just useful to store elastic energy; it also helps to make a segmented leg safe and robust when faced with external perturbations.

In the following two sections we will deal with the global leg function, i.e. how a spring-like leg can be controlled to obtain stable locomotion as observed in running or walking. We provide evidence that spring-like leg operation may also be useful in facilitating the global leg function, i.e. the method in which the body utilizes limbs for stable locomotion.

4 Running with Elastic Legs

The movement of a single leg during walking and running is characterized by a series of contact and swing phases. At lower speeds humans generally choose to walk whereas at higher speeds running is preferred. During the stance phase of running, the leg compresses until midstance and then extends until the leg leaves the ground. The force generated by the leg is approximately proportional to the amount of leg compression [4, 3]. This relation provides the basis for the concept that leg stiffness is the parameter describing that the ratio between leg force and leg compression remains constant. This concept leads to the spring-mass model which describes the movement of the center of mass based on a spring-like leg operation during the stance phase of running [1].

For certain combinations of leg stiffness k and leg angle of attack α_0 cyclic motion of the center of mass (COM) can be observed (Fig. 5A). Interestingly, cyclic movement can also be achieved for slightly different initial conditions.

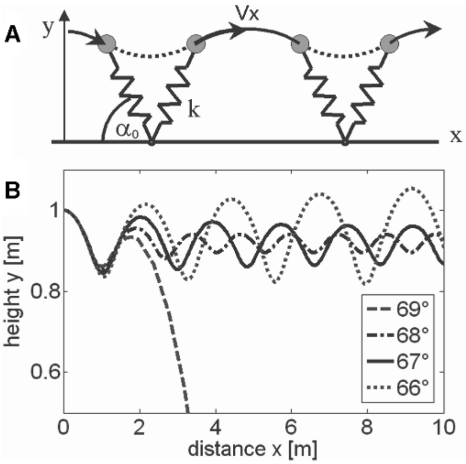

Fig. 5. Spring-mass running. (**A**) For certain combinations of leg stiffness k and angle of attack α_0 a cyclic movement of the center of mass can be found. (**B**) Different angles of attack can result in stable running patterns (here $\alpha_0 = 67^o$, 68^o with leg stiffness $k = 20$ kN/m, body mass $m = 80$ kg, leg length $l = 1$ m). Steeper angles overshoot a step resulting in failure at the proceeding step ($\alpha_0 = 69^o$) whereas flatter angles decelerate the movements until forward velocity goes to zero ($\alpha_0 = 66^o$). With leg retraction, e.g. increasing α_0 prior to landing, the angular adjustment can vary much more without losing running stability (not shown here, for details see [24])

The movement of the center of mass approaches a steady state after a couple of steps without modifying the landing leg angle α_0 (Fig. 5B). However, even when modifying the angle of attack α_0 stable running can be observed, although the COM trajectory has adapted slightly. Hence, spring-mass running is self-stabilizing and robust with respect to changes in the initial conditions and model parameters (e.g. leg angle of attack, leg stiffness, system energy). The adjustment of leg stiffness and angle of attack is not unique. At a given running speed, different combinations are possible (Fig. 5B) and result in specific running styles; for instance, in terms of step length or step frequency. This prediction agrees with experimental results [23]. With increasing speed, the range of successful combinations of leg angle and leg stiffness is even increased.

In contrast, at low speed (less than 3 m/s) no stable running is predicted with the constant angle of attack control policy at any leg stiffness. However, animal or human running reveals that the leg angle is not kept constant prior to landing [5]. In fact, a backward rotation of the leg with respect to the body is observed. Introducing this early leg retraction we find an increased stability in spring-mass running at low speeds [24]. Even larger variations in internal or external conditions (e.g. a change in ground level of 50 percent leg lengths) can be managed when leg retraction is used.

In this section we introduced two global leg control strategies for running with compliant legs: constant angle of attack and leg retraction. We found that for a given system energy spring-mass running is stable for various combinations of leg stiffness k and angle of attack α_0. For higher running speeds and by employing leg retraction the region of stable running (leg stiffness and leg angle adjustment) is largely enhanced.

In a recent study, the spring-mass model for running was extended to a rigid body model in the vertical plane and analyzed based on an analytical approximation neglecting gravity during the stance phase [11]. The results support the identified strategies for stable running with a fixed angle of attack policy. Furthermore, it is argued that at high running speeds the domains of attraction become smaller (i.e. the system is less robust with respect to perturbations of the center of mass trajectory) leading to a demand for more elaborated control methods. One possible method could involve the adaptation of leg stiffness to flight time duration (e.g. due to muscle preactivation) similar to the strategy of leg retraction. Therefore, an integration of muscular mechanisms into the analysis of running stability would be helpful.

5 From Running to Walking

So far only a single leg was considered in the analysis of spring-mass running. As a next step we generalize the model to bipedal locomotion. Does the concept of spring-like leg operation hold only for running with single support phases? What happens to the system dynamics if more than one leg is in contact with the ground at the same time?

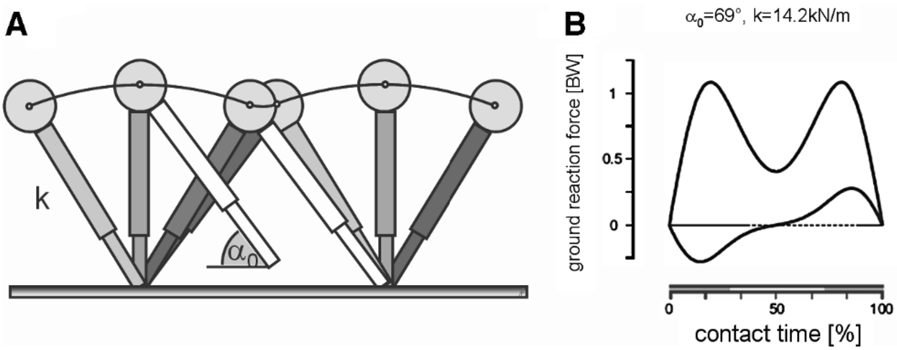

Fig. 6. Spring-Mass Walking. (**A**) For certain combinations of leg stiffness k and angle of attack α_0 a cyclic movement of the center of mass can be found. (**B**) The single leg force patterns (*upper line*: vertical force, *lower line*: horizontal force) resemble that found in human and animal walking [9]

In a previous simulation study we investigated the behavior of a bipedal spring-mass model [9]. This model consists of two massless springs (leg stiffness k) and a point mass representing the center of mass (COM). During the single support phase one leg spring remains in contact with the ground while the other is positioned at a constant angle of attack. If the COM reaches the corresponding landing height of the second leg before the first leg leaves the ground a double support phase occurs (Fig. 6A). Although slightly more complex than the previous running model, stable solutions can again be found using different combinations of leg stiffness k and angle of attack α_0. In contrast to the single leg model, stable solutions with double support phases can only be found for low system energies (forward speed lower than about 1.4 m/s). The single leg forces predicted by the bipedal spring-mass model are very close to the observed patterns in human and animal walking (Fig. 6B). The corresponding maximum walking speed is only slightly above the preferred walking speed observed in humans. This suggests higher control efforts at higher walking speeds. Hence, mechanical stability and therefore a relaxed control (rather than metabolic considerations) could be important criteria to explain the preferred walking speed.

At high energies (forward speed larger than about 3 m/s) the previously observed running pattern is found if the leg is allowed to contact the ground after take-off of the opposite leg. Thus, the bipedal spring-mass model can both stable walking and running on a single mechanical system. There is an energetic gap between both gaits which can only be accessed by a more complicated control strategy (e.g. leg retraction of the swing leg). The model suggests that walking and running are two natural and self-stabilizing behaviors of a simple mechanical system. This concept has strong implications on the design and control of legged systems in general. Leg compliance is not only a strategy to facilitate control; it might also be the origin of the existence of natural gaits. Furthermore, it resolves the issue of collision avoidance which was addressed recently in studies on inverted pendulum walking [20].

In the last sections we examined consequences of compliant leg operation on a global scale. We found that the two fundamental gaits of legged locomotion are natural behaviors of elastic legs attached to a common center of mass. In the next section simple legged robots are introduced. How does the behavior of a constructed leg compare to the conceptional models for legged locomotion presented in the last four sections?

6 Exploring Simple Legged Robots

Elastic leg behavior can elucidate design and control strategies used in legged systems. However, all models presented so far are based on computer simulations or analytical calculations. While the model-based predictions have been compared to results from biology, as discussed in Sects. 3, 4 and 5, it was decided that further validation under real-world conditions was necessary. Therefore, we built a series of very simple legged robots to better understand the pros and cons of our theoretical models, examining their validity and the underlying assumptions, and to examine any overlooked elements.

What should a simple legged robot look like? A good example can be found in the pioneering work of Raibert and his coworkers [19]. These robots are made of elastic legs (pogo sticks) which are controlled in such a manner as to regulate hopping height, body speed and pitch at desired values. We found the construction of a pogo stick leg still "delicate" from the mechanical point of view (e.g. due to constraint forces perpendicular to the leg axis) and decided consequently to start with a simple two-segment leg (Fig. 7A), instead.

6.1 Robot Testbed with Elastic Two-Segment Leg

Our goal is to explore the natural dynamics of a two-segment elastic leg during forward hopping. The movement of the robot (Fig. 7A) is constrained by a metal boom which allows the robot to only move in vertical and horizontal direction. Body pitch movements are not allowed to keep the mechanical system as simple as possible. The focus of this approach is to better understand how legged systems are organized. The movement of the leg is driven by a servo motor between the body and the upper leg segment (thigh). The motor introduces a sinusoidal oscillation defined by oscillator frequency f, angular amplitude A and offset angle O. Taking a maximum angular velocity ω_{MAX} of the motor (1 rotation/s) into account, the amplitude A can be calculated depending on the frequency f with

$$A = \omega_{MAX}/(2\pi f) \ . \qquad (1)$$

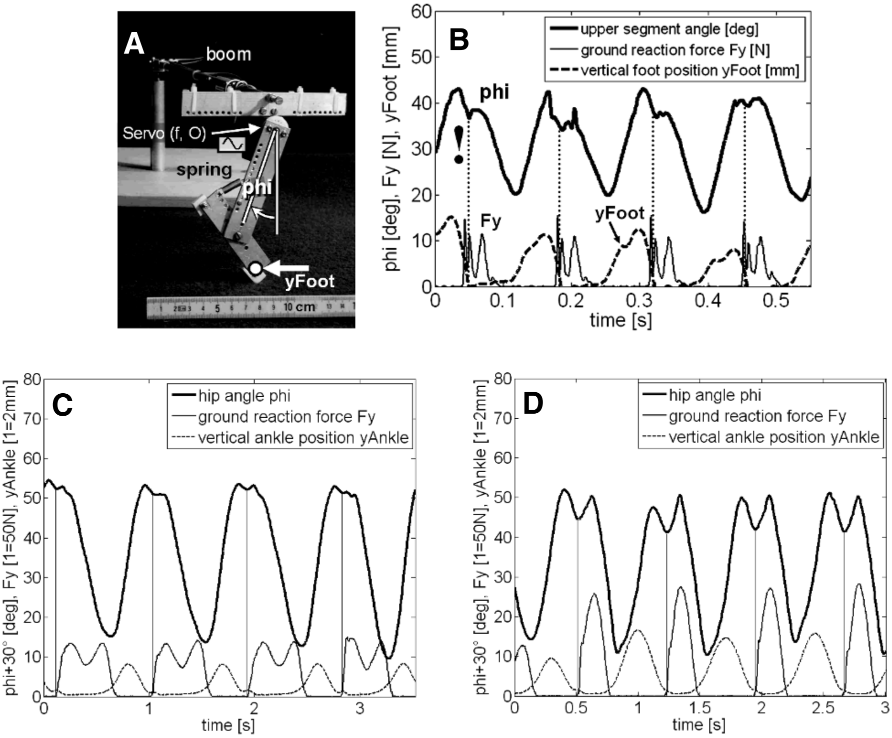

Fig. 7. (**A**) The "Fujubot" robot, with an elastic two-segment leg kinematically driven at a sinusoidal trajectory using a hip-mounted servo motor. (**B**) Experimental data for stable robot hopping. The angle of the upper segment (phi) is predefined by the motor control. At touch-down (*dotted vertical lines*) retraction of the upper segment is briefly interrupted, but recommences immediately afterwards. (**C**) Experimental data on human walking and (**D**) running at 2 m/s

This robot follows the rapidly prototyped, minimalist approach to design ("cheap design" robots, [16]), avoiding high-end or high-precision components and advanced control approaches. For instance, the upper leg segment does not follow the desired angular trajectory of the servo motor (Fig. 7B). Every time the leg hits the ground leg retraction is interrupted. This is due to the fact that the leg joint flexes shortly after landing impact. Comparing this observation with experimental data in human running and walking we find the same phenomenon. At a forward speed of 2 m/s the relative timing of protraction and retraction of the upper limb is very similar between walking and running. Both in the robot and in human running touch-down occurs shortly after the initiation of limb retraction. This is in agreement with the predicted role of leg retraction for stability [24].

To investigate the influence of an enforced leg retraction after touch-down, we implemented a higher torque motor using very stiff coupling of the motor

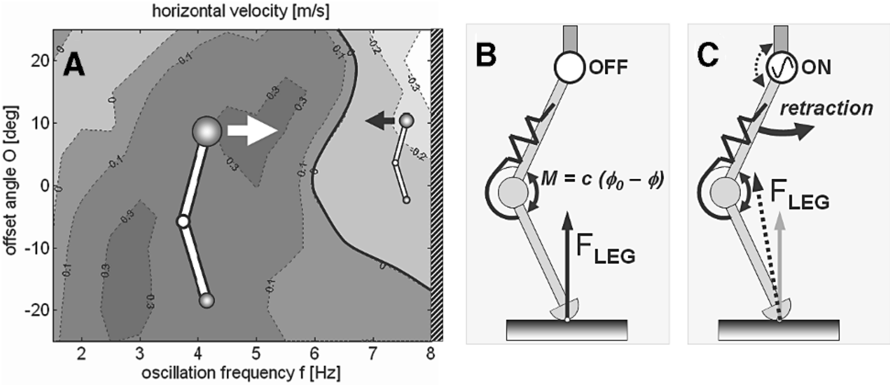

Fig. 8. (**A**) Dependency of hopping direction on control parameters (oscillation frequency *f*, offset angle O) of the servo motor. (**B**) With no hip actuation the leg force F_{LEG} merely depends on joint torque M and leg geometry. (**C**) Leg force is enhanced compared to (B) if the hip retracts actively (hip extension torque). The opposite is true if leg retraction is pointing to the left, in which case the leg force is reduced

to the hip joint. As a result the boom keeping the upper body upright broke. Consequently, a more compliant coupling was inserted between the motor and the hip joint, imitating the biological function of tendons in hip muscles.

The robot demonstrates a variety of behaviors depending on the selected oscillator frequency f and offset angle O. Surprisingly, at low oscillation frequencies, the hopping direction is not as expected, namely opposite to the leg joint (Fig. 8A). This movement could well be compared to that of a hopping bird. This behavior is not very sensitive to changes in the control parameters. At higher frequencies (above 6 Hz) a more human-like movement is observed. Then, the leg joint points forward (similar to a human knee). At an intermediate region hopping in place is observed with no substantial horizontal movement.

Why does the robot change its movement direction depending on the selected control frequency? To approach this question the effect of active limb retraction on the leg dynamics is considered in Figs. 8B and 8C. For simplicity, we focus on a static approach neglecting all dynamic effects, i.e. due to segmental accelerations, joint damping, or torques at the foot point. With no retraction (zero hip torque), leg force is directly dependent on limb configuration. This is a consequence of the rotational spring which relates joint torque to joint angle.

If the hip is actively contributing to limb retraction (Fig. 8C), leg force is increased or decreased depending on the geometrical relation between leg joint torque and hip torque. In bird-like hopping, leg force is reduced whereas in human-like hopping the force is increased. As a consequence of this increased (or decreased) leg force, the natural frequency of the hopping system is changed, i.e. an increased leg force to some extent imitates a stronger (stiffer) leg associated with a higher step frequency. This is a well known dependency for the spring-mass model.

Hence, with compliant legs movement direction can be encoded as a frequency signal. At this level, the detailed trajectories of the limb segments are not required to control the different directions of movement. Stable hopping is robust with respect to variations in the control parameters (oscillation frequency, offset angle). This is in line with the self-stabilizing mechanisms of spring-mass running. It remains to be investigated in detail how the control parameters influence the angle of attack and the effective leg stiffness. Furthermore, we found that elastic joint behavior is important in dealing with impacts (e.g. touch-down) avoiding damage to the actuator. A simple harmonic oscillation in the hip is sufficient to obtain stable hopping movement. The observed protraction and retraction plots of the upper limb are very similar to those observed in human walking and running. This encouraged us to build bipedal robots imitating the hip strategy of the one-legged hopping robot. Based on this experimental platform we will extend the concept of spring-like hopping to compliant walking.

6.2 Bipedal Robot

The bipedal spring-mass model indicates that compliant legs may facilitate stable running and walking. Does this mean that walking is just running with double support phases? We approach this question by comparing experimental data on human walking and running with the behavior of a simple bipedal robot. We will demonstrate that leg compliance is useful in generating stable walking movements. The analysis of the three-segment model (Sect. 1) indicates that elastic joint operation may lead to a synchronous operation of the leg joints. Such behavior can be found in human running (Fig. 9) where during stance both knee and ankle joint flex and extend in parallel. In walking this situation is not found: the knee joint extends during midstance and the ankle joint extends only at the late portion of the stance phase when the knee joint has returned to flexing. The desired function of a mechanical spring to store and release elastic energy does not seem to be fulfilled by a walking leg. The high level of coordination between knee and ankle joint in running allows an efficient push-off phase after midstance. The biarticular m.gastrocnemius transfers the rotational energy of the knee joint to the ankle which in turn is capable of generating a rapid leg extension. In walking this coupling is not found. The extension of the knee joint does not lead to a push-off phase because the ankle joint does not follow the knee extension. In the extended configuration the knee is not able to contribute to leg lengthening but it has a significant contribution to leg rotation. In fact, the effect of thigh retraction on leg retraction is reduced by knee extension and (later) supported by knee flexion. As a result the thigh is already protracting before the leg leaves the ground (Fig. 9A).

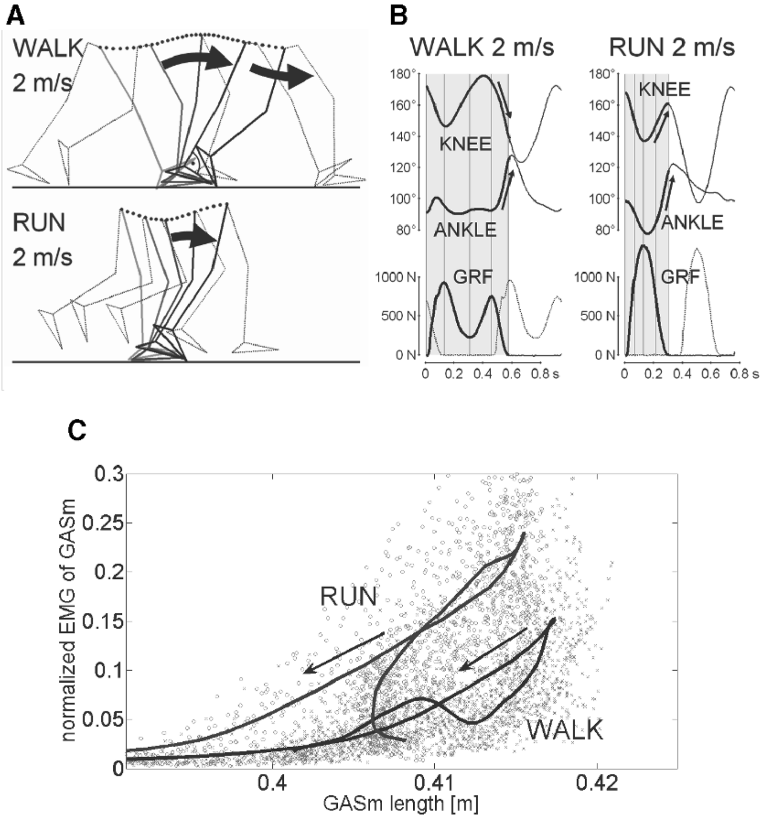

Fig. 9. (**A**) Leg kinematics in human walking and running at the preferred transition speed (2 m/s). (**B**) Knee and ankle joint kinematics and vertical ground reaction forces corresponding to (A). (**C**) Muscle activity vs. muscle length of m.gastrocnemius medialis (GASm) of one subject during walking (41 steps, circles) and running (45 steps, crosses) at 2 m/s. *Thick lines* represent mean tracings for walking and running. Muscle length is calculated based on knee and ankle angle data [15]

If the rotational energy during knee extension (at midstance in walking) is not used for push-off, how can this energy be reused for locomotion? With continuous thigh retraction during stance phase (e.g. due to active hip retraction) the m.gastrocnemius gets stretched and can use the knee rotation at a later time to contribute to ankle extension. Hence, the rotational energy of the knee during midstance could still be reused for push-off triggered by the amount of leg rotation during stance phase. Therefore, we hypothesize that in walking the nominal length of the biarticular m.gastrocnemius should be longer than when compared to running.

To test this hypothesis we analyze the activity of m.gastrocnemius medialis (Fig. 9C) and compare it to the estimated length of the muscle [15]. We find

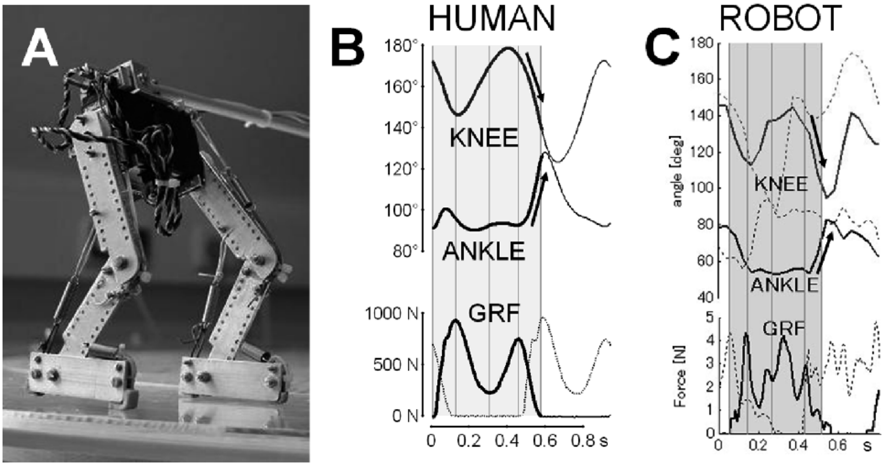

Fig. 10. (**A**) The "JenaWalker" bipedal robot, equipped with compliant legs. (**B**) Joint kinematics of knee and ankle joint and ground reaction forces (GRF) during human walking and (**C**) during robot walking. Dotted curves indicate opposite leg

that muscle activity is dependent on muscle length and gait. In walking the EMG is active at greater muscle length as compared to running. This indicates that walking could take advantage of elastic biarticular structures spanning knee and ankle joint as also suggested in a previous simulation study [2].

To test this idea the bipedal "JenaWalker" robot was developed (Fig. 10A, [17]). In order to investigate this gait-specific interplay between ankle and knee joint we decided to use three-segment legs. A biarticular spring was installed between knee and ankle joints, simulating the function of m.gastrocnemius. Furthermore, two additional "muscles" were required in the leg: one foot flexor (m.tibialis anterior) and one biarticular knee extensor and hip flexor (m.rectus femoris). This combination of elastic structures in a three-segment leg turned out to be sufficient to generate stable locomotion. In agreement with our experimental data on human walking we kept the hip control the same as in the hopping robot (i.e. a simple harmonic oscillation).

An example of the leg kinematics and the ground reaction forces for stable walking is given in Fig. 10C. The robot is able to reproduce the experimentally observed knee and ankle joint kinematics (Fig. 10B). It is important to note that no effort was made to optimize the leg kinematics or the ground reaction forces to fit biological data. The criterion used for optimization is a steady periodic movement pattern. The robot is able to walk, hop and run specified by a corresponding motor adjustment. For instance, walking is robust with respect to changing step frequencies. Running is only possible for high offset angles with the legs operating in front of the body. This is due to the fact that the leg cannot bend freely during the swing phase. With synchronous hip function, hopping was found.

The legged robots presented here demonstrate that stable walking and running can be observed with compliant legs and simple harmonic oscillations at the hip joint. The movements are robust although both design and control are very simple. In the three-segment leg, the function of knee and ankle joint is gait-specific. The biarticular muscles could play an important role in synchronizing the internal leg function depending on the selected gait. *Running* can be considered as a gait with fast leg compression and fast leg rotation. The leg rotation (retraction) is mainly provided by hip extension and knee flexion (plus late ankle extension). Due to synchronized operation of knee and ankle, the high joint angular velocities are slowed down in the biarticular m.gastrocnemius. *Walking* is a gait with slow leg compressions and slow leg rotation. Leg rotation is reduced by knee extension during midstance but supported by knee flexion at early and late stance phase. As a consequence, the upper limb can already start protraction while the leg is still on the ground. This allows the hip control to still follow a harmonic oscillation despite a duty factor larger 0.5. Due to the out-of-phase operation of knee and ankle, the slow joint movements are accelerated in the biarticular m.gastrocnemius. Further research is required to better understand these intersegmental dynamics in walking and running at different speeds and environmental conditions.

7 Conclusions

In this paper we summarized several simple biomechanical models and “cheap” design robots describing legged locomotion. The common design principle was to reduce the systems to a minimal configuration which allows for a systematic investigation of the underlying mechanisms of legged locomotion. The introduction of compliant structures and the search for self-stabilizing mechanisms revealed to be effective tools to identify natural movement patterns and relaxed control strategies.

It turned out that walking and running can be described as two natural movement patterns of one mechanical system with elastic legs. The organization of the segmented leg is largely supported by elastic structures spanning one or more joints. For properly designed legs, the control is largely simplified and could be reduced to an adjustment of hip oscillators in our legged robots. In the future, we aim to identify leg designs which are equally suited for both human-like walking and running. Therefore, a better understanding of the gait selecting mechanisms will be required.

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