A. Seyfarth
F. Iida
University of Jena, Locomotion Lab
Dornburger Str. 23, D-07743 Jena, Germany
email: andre.seyfarth@uni-jena.de, iida@csail.mit.edu

R. Tausch
M. Stelzer
O. von Stryk
Technische Universität Darmstadt,
Simulation and Systems Optimization Group
Hochschulstrasse 10, D-64289 Darmstadt, Germany
email: {tausch, stelzer, stryk}@sim.tu-darmstadt.de

A. Karguth
TETRA – Gesellschaft für Sensorik,
Robotik und Automation mbH Gewerbepark
"Am Wald" 4 – D-98693 Ilmenau, Germany
email: aku@tetra-ilmenau.de

Towards Bipedal Jogging as a Natural Result of Optimizing Walking Speed for Passively Compliant Three-Segmented Legs

Abstract

Elasticity in conventionally built walking robots is an undesired side-effect that is suppressed as much as possible because it makes control very hard and thus complex control algorithms must be used. The human motion apparatus, in contrast, shows a very high degree of flexibility with sufficient stability. In this research we investigate how compliance and damping can deliberately be used in humanoid robots to improve walking capabilities. A modular robot system consisting of rigid segments, joint modules and adjustable compliant cables spanning one or two joints is used to configure a human-like biped. In parallel, a simulation model of the robot was developed and analyzed. Walking motion is gained by oscillatory out-of-phase excitations of the hip joints. An optimization of the walking speed has been performed by improving the viscoelastic properties of the leg and identifying the appropriate hip control parameters. A good match was found between real robot experiments and numerical simulations. At higher speeds, transitions from walking to running are found in both the simulation as well as in the robot.

KEY WORDS—locomotion, compliant legs, walking, running, control, optimization

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Figures 1–4, 6, 7, 9, 11, 13 appear in color online: http://ijr.sagepub.com

1. Introduction

The control of human walking and running is considered a challenging task. The musculo-skeletal system consists of many segments connected with joints of different degrees of freedom and spanned by highly redundant muscle-tendon groups of different morphologies. Furthermore, a substantial portion of the body is compliant or softly attached to the skeleton. With respect to the standard approaches in control theory this seems to be an almost unsolvable task. This situation appears to be even worse at higher speeds as in running or sprinting. Here, the sensory noise may further limit the controllability of the system in terms of potential feedback mechanisms.

A promising way out of this unfortunate situation was demonstrated by McGeer's passive dynamic walking concept (McGeer 1990). He built a purely mechanical bipedal robot which was able to walk down a shallow slope without any actuation or sensory control. Based on this fascinating approach several walking robots with little or no sensory feedback have been developed over the last decade (Collins et al. 2005). One drawback for all of these walking robots is the requirement for complete knee extension during stance phase which limits the walking pattern to one preferred speed and frequency. In reality, however, humans are quite able to walk at a large range of speeds (0–3 m/s) and adjustable step frequencies.

This adaptability of gait patterns becomes even more evident for the transition from walking to running. Here, it is widely accepted that the leg behavior should be compliant and not stiff as suggested by the passive dynamic walkers (Cavagna et al. 1964• Blickhan 1989). This idea has been successfully demonstrated in the first hopping robots of Raibert (1986). Taking advantage of the compliant leg dynamics, these robots were able to stabilize several gait patterns based on simple control strategies of body posture and speed. Since then, the development of walking machines and running robots was separated due to the two different leg design approaches: stiff legs for walking movements and compliant legs for running and hopping.

In a recent simulation study (Geyer et al. 2006) we found that walking and running could well rely on the same concept of compliant leg behavior. Assuming a simple spring-like leg function with leg force proportional to the amount of leg compression, stable walking and running patterns are predicted for appropriate touch-down angles of the stance leg. At low speeds, walking with double-support phases and double-humped force patterns turns out to be a stable gait pattern which is quite robust to variations in leg stiffness or landing leg angle. In contrast, once a critical minimum speed is exceeded, running movements with single-humped patterns of the ground reaction force occur with largely adjustable step frequencies and unlimited speed. The stability of these gait patterns can be roughly compared to the self-stability of a bicycle at high speeds. Even without a rider the bike keeps going in an upright position and can negotiate uneven ground or smaller obstacles.

This is similar to running. The faster we run the less crucial is the adjustment of the leg properties, namely the leg stiffness and the leg orientation at touch-down (Seyfarth et al. 2002). Therefore, it might be possible to construct a mostly passive running robot with little or no sensory feedback. At the same time, the robot might be able to walk stably at moderate speeds. In a first simple bipedal robot (Iida et al. 2006) we were able to demonstrate emergent walking patterns based on a segmented leg design with elastic structures spanning hip, knee and ankle joints. Here, we aim to further investigate potential elastic mechanisms to enable human-like walking and running. Therefore, two approaches were used in parallel. First, we built a novel bipedal robot with passive elastic three-segment legs and two DC motors driving the hip joint (cf. Figure 1). Second, a simulation model was implemented to identify appropriate leg designs and motor control parameters for stable locomotion.

Fig. 1. The JenaWalker II bipedal robot testbed.

2. Things to Learn from Human Legs

The legs of all current humanoid robots which are able to reliably perform a variety of different walking motions in experiments (as ASIMO (Hirai et al. 1998), HRP-2 (Kaneko et al. 2004), Johnnie (Loeffler et al. 2003) or QRIO (Ishida et al. 2003)) consist of rigid kinematic chains with a number of revolute joints (or combinations of them) using electrical motors of high performance and with rigid gears for rotary joint actuation. Although small flight phases have already been achieved for some humanoid robots in experiments (QRIO, ASIMO), the demonstrated performance is far from natural jogging or running (Co 2005).

Elasticity in conventionally built articulated robots is considered an undesired side-effect that is being suppressed as much as possible because it introduces high challenges for accurate position or trajectory tracking control. The human motion apparatus in contrast is not equipped with rigid rotational single-joint actuators. Instead it uses highly redundant and compliant actuators. This results in a high degree of flexibility and stability during human locomotion, which is supported by local properties of the musculo-skeletal system and reflexes.

The overall target related to the work in this paper is to investigate how compliance and damping can deliberately be used in humanoid robots to extend the range of locomotor capabilities as there is no humanoid robot design yet known which enables slow walking and real running with one and the same leg design. Our approach is to introduce the locomotion-stabilizing properties of muscle-tendon complexes and reflexes into the mechanical structure of robots, thereby reducing the necessity for complex, full-feedback control. As a

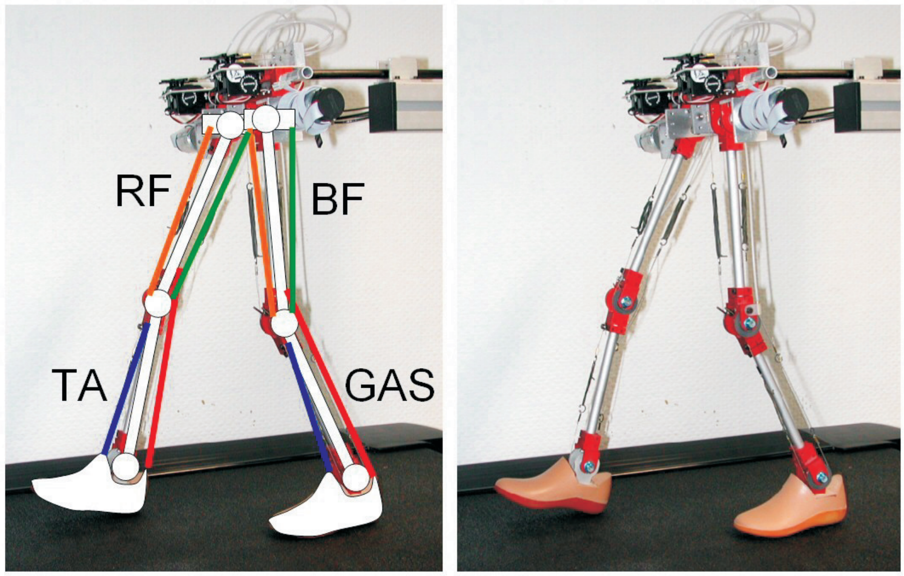

Fig. 2. The arrangement of elastic structures spanning the ankle, knee and hip joints in the JenaWalker II.

consequence, the degrees of freedom that would otherwise be used for stabilization using control algorithms thus can be used to modify the walking pattern (e.g., changing body height by adjusting nominal knee flexion) without losing stability while keeping the same basic gait pattern.

3. Mechanical Structure and Properties of the JenaWalking II Robot

A newly developed modular robot system consisting of rigid segments, joint modules and adjustable elastic strings spanning hip, knee and ankle joints is used to configure the human-like biped JenaWalker II (total robot mass: about 2 kg). Each leg (hip height 45 cm) consists of three segments including thigh, shank and a prosthetic foot (SACH child foot, Otto Bock). Similar to the first biped robot (JenaWalker (Iida et al. 2006, 2008), see Video 1 at time 0:06), four major leg muscle groups are represented in the robot by elastic structures (see Figure 2): tibialis anterior (TA), gastrocnemius (GAS), rectus femoris (RF) and biceps femoris (BF). Except for the TA, all muscle groups span two joints leading to an inter-joint coupling within the leg. Furthermore, friction in the cables spanning the ankle joint contribute to damping in this joint. This damping is necessary to avoid vibrations of the foot during swing phase.

Servo motors above the hip joints are used for tuning the rest lengths of the springs representing the action of GAS, RF and BF resulting in postural adjustments of knee and ankle joints. At the hip, sinusoidal oscillations (frequency f, amplitude A, offset angle O) are introduced by DC motors using PD control imitating the alternating activity of the hip joint muscles during locomotion. The compliance of the elastic coupling between the DC motor and the hip joint is chosen to allow a joint play of about 10–15 degrees. This was identified to be useful to reduce impacts on the upper body and it results in hip angle trajectories comparable to human walking and running (Seyfarth et al. 2006).

It is important to note that the mechanical self-stabilization of leg movement plays an important role, because the actual trajectory of the thigh with respect to the upper body deviates from the given sinusoidal pattern of the DC motor. Thus the hip motor only determines the frequency f and the approximate amplitude A of the hip oscillation. The combination of both parameters, namely the product $A \cdot f$, approximately prescribes a desired forward speed. For simplicity, the upper body is restricted to move in the sagittal plane• trunk rotation (pitch) is not allowed in the current state of the robot. Furthermore, the robot is installed on a motorized treadmill in order to facilitate the analysis of steady-state locomotion.

4. Behavior of the Walking Robot

After careful tuning of the compliant cables simulating GAS, TA, BF and RF the robot is able to exhibit stepping movements introduced by the hip motor (see Video 1). Interestingly, even at zero speed a movement pattern similar to human walking on place is observed. The servo motors are capable of changing the posture of the legs, i.e. changing the amount of knee joint flexion or ankle joint extension (plantar flexion) during walking.

Fig. 3. Walking sequence of JenaWalker II at moderate speed.

With increasing speed, the robot is able to adapt the leg movements when tuning the frequency and the amplitude of hip oscillation correspondingly but without changing the adjustments of the compliant cables spanning hip, knee and ankle joints (Figure 3). At a given speed, the hip frequency can be tuned by a factor of about two by simultaneously adapting the amplitude of hip oscillation. At approximately 1 m/s the maximum walking speed is observed. At this speed, a transition into jogging is achieved by further increasing the hip frequency f at the cost of the amplitude A. It must be stated that due to torque limitations of the servo motors only jogging with almost straight knee joints is possible. To compensate for this disadvantage, an extended foot position is used by tuning the GAS servo accordingly. By doing so, short flight phases can be observed.

By changing the phase relation of the hip motors from out-of-phase in walking and running to in-phase, bipedal hopping movements can be observed. Here, both knee joints act together generating enough force to dynamically support the body even at flexed knee positions. This demonstrates the elastic leg behavior which can equally generate walking as well as jogging or bouncing gaits.

5. Numerical Optimization of the Walking Motion

A detailed MATLAB/SimMechanics (The Mathworks, Inc.) computational model of the robot including a 2D ground contact model has been established. The size of the model was scaled up to a human body (body mass $m = 80$ kg, leg length $l = 1$ m) to allow further comparisons with human experiments. An optimization of the walking speed has been performed numerically for the parameterized walking motion: the frequency f, offset angle O and the maximum rotational speed $\omega_{\max}$ of the hip motor, the stiffness, damping and offset angle of the ankle and of the knee, and the stiffness and offset angle of the RF and of the GAS springs (Figure 2) have been optimized on (1) unconstrained implicit filtering (Abramson 2002) and (2) the Nomad method (Gilmore and Kelley 1995). The latter method includes the ability to handle nonlinear constraints.

An initial walking motion has been established using a manually adjusted parameter set. The speed of the initial motion was 34% of the estimated reference speed ($v_{\text{ref}} = \omega_{\max} \cdot l$) while the best motion obtained by numerical optimization of the parameterized simulation model resulted in a walking speed of more than $100\% \cdot v_{\text{ref}}$. The corresponding motion pattern exhibited flight phases, i.e. the transition from walking to jogging has been observed as a natural extension of increasing walking speed for a human-like three-segmented elastic leg design.

6. Numerical Results

As a first solution for the numerical optimization, a reasonable set of hand-tuned parameters is used. With these parameters, a walking speed of about 1 m/s is achieved as shown in Figure 4. After the starting phase of locomotion, the speed of the robot converges to the final value. The hip torques are of relatively high values and reach up to 400 N m (Figure 5). The motion is symmetric between both legs. The left leg is in ground contact from 10.23 s to 11.10 s and the right leg is swinging forward between 10.59 s and 10.72 s. Hence, the swing phase is much shorter than the contact phase. During contact, the hip is first exerting positive extending torques (e.g. around 10.5 s) followed by negative flexing torques (e.g. 11.0–11.2 s).

In the following paragraphs, three optimization studies based on unconstrained implicit filtering (study 1) and based on the Nomad method (Studies 2 and 3) are presented. In the first study, the motion is optimized for speed only, which leads to high torques of the hip motors. In the second study, the motion is optimized for speed and the hip torques were limited to a reasonable value. Finally, the motion is optimized for minimizing hip joint torques and the speed was limited to be higher than two-thirds of the speed achieved in the second study.

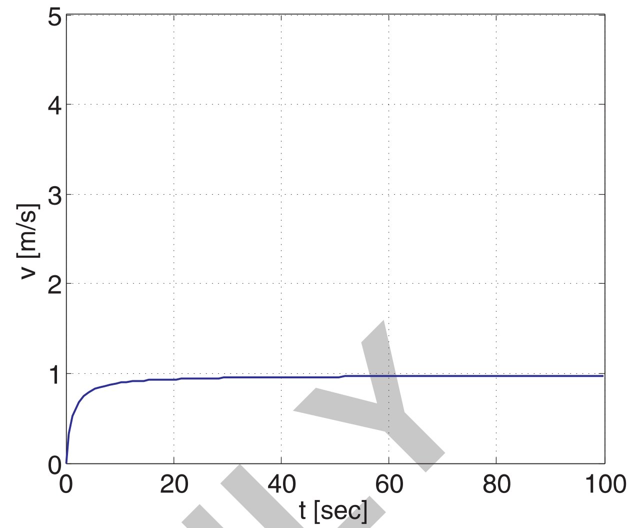

Fig. 4. Walking speed with initial parameter set.

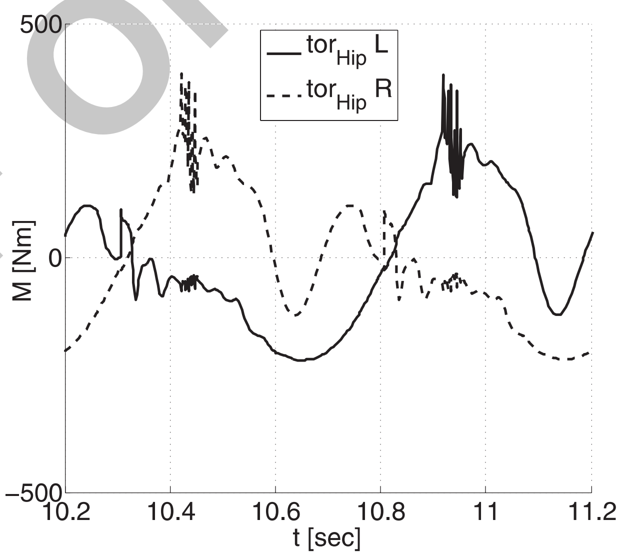

Fig. 5. Hip torques for walking motion with initial parameter set.

In Study 1 (Figures 6, 7 and 8, see Video 1 at time 0:27), we optimize only for speed starting at the initial solution. The observed increase of speed (up to 1.6 m/s) is associated with increase of hip torques (maximum 700 N m). This optimized configuration found by the implicit filtering method reduces foot sliding resulting in a quite natural walking motion (see Figure 6). Investigations showed that the walking speed could be improved even further.

In Study 2 (Figures 9 and 10), we address the issue of high hip torques by bounding these torques to be less than 500 N m. The resulting walking motion obtained by the Nomad method outperforms the result from Study 1. The maximum speed pre-

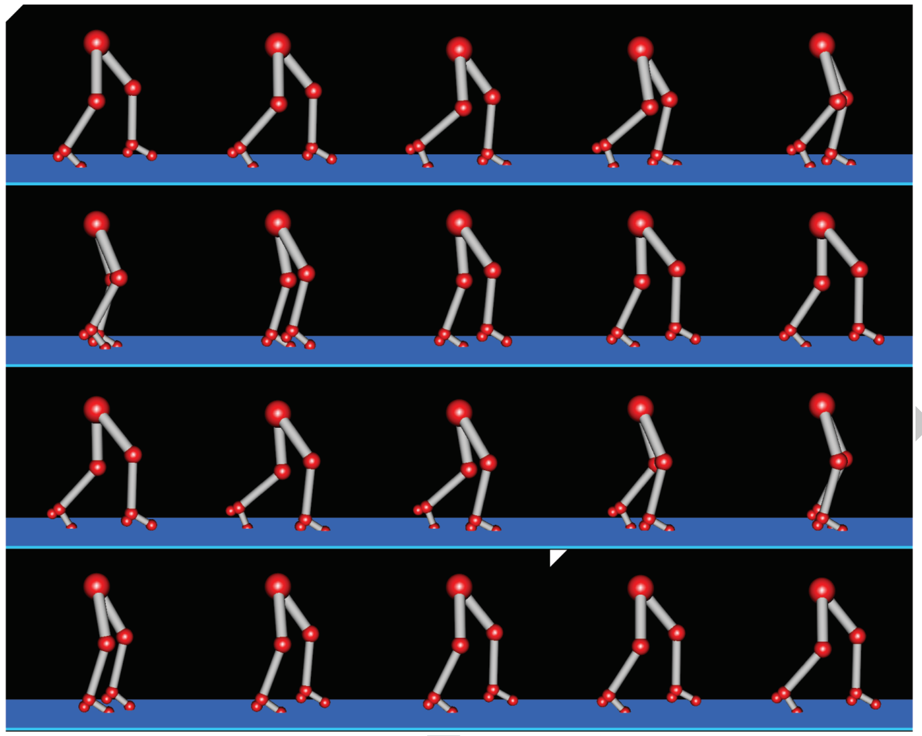

Fig. 6. Walking sequence with parameter set optimized for speed using the implicit filtering method (Study 1).

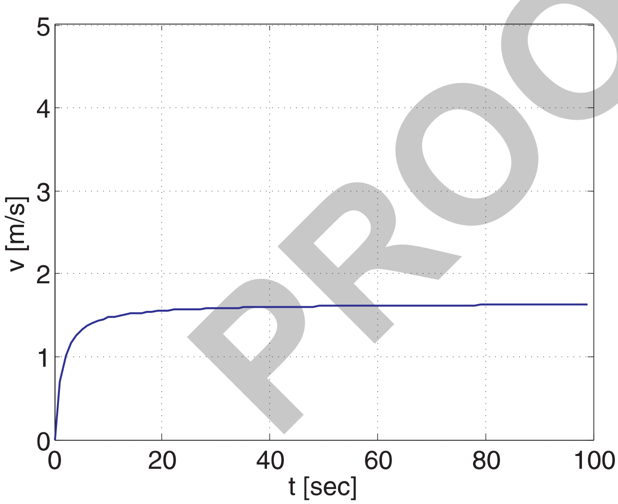

Fig. 7. Walking speed with parameter set optimized for speed using the implicit filtering method (Study 1).

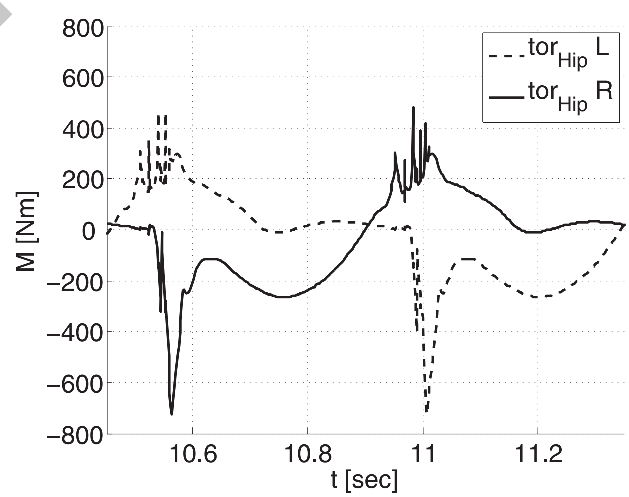

Fig. 8. Hip torques for walking motion with parameter set optimized for speed using the implicit filtering method (Study 1).

dicted by the model is now 3.6 m/s taking advantage of flight phases. The functions of the two legs are now asymmetric as indicated by the torque patterns (e.g. around 10.3 s and 10.65 s in Figure 10) which are not identical. This difference also remains in further steps.

In comparison to the solution of Study 1, the ankle joint of Study 2 is now stiffer with a more extended rest angle. Hence, foot contact occurs only at the ball and no longer at the heel (in contrast to the observed movement in natural walking and in the JenaWalker II robot). At the same time, the knee joint

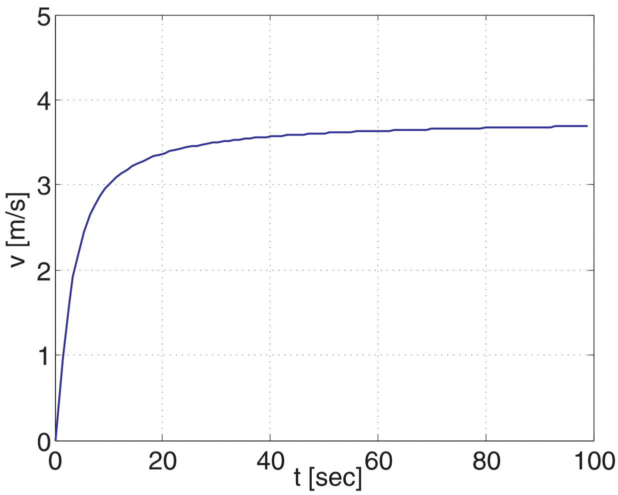

Fig. 9. Locomotion speed with parameter set optimized for speed and bounded torques using the Nomad method (Study 2).

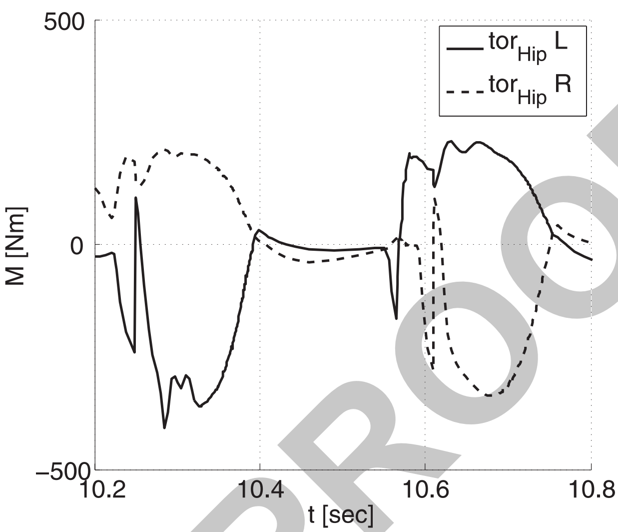

Fig. 10. Hip torques for gait pattern with parameter set optimized for speed and bounded torques using the Nomad method (Study 2).

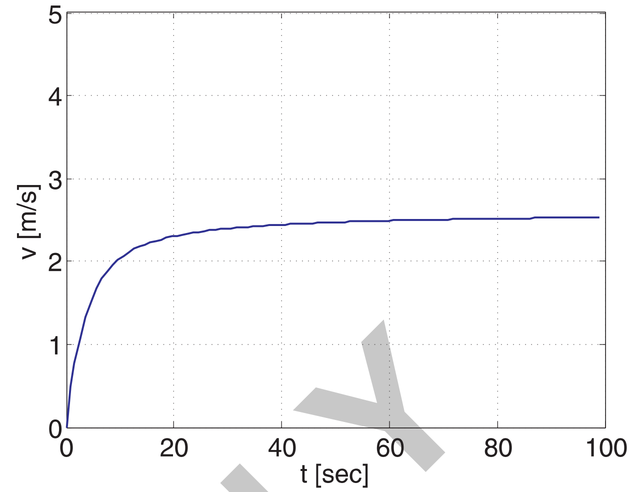

Fig. 11. Locomotion speed with parameter set optimized for low hip torques and bounded velocity using the Nomad method (Study 3).

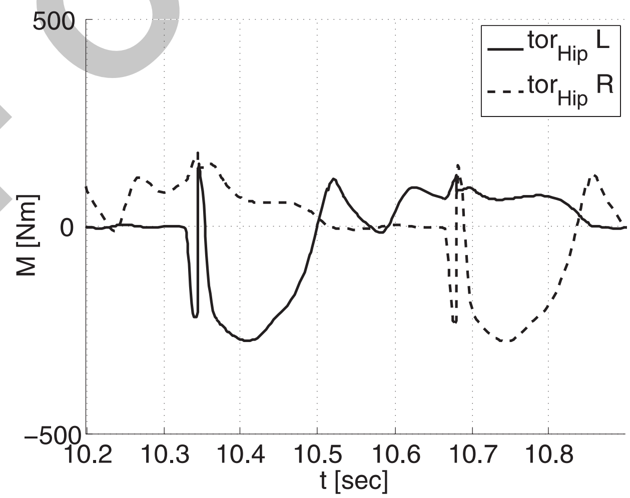

Fig. 12. Hip torques for gait pattern with parameter set optimized for low hip torques and bounded velocity using the Nomad method (Study 3).

is more compliant (half stiffness) but has the same nominal angle as in Study 1. Surprisingly, the hip motor control parameters remained almost unchanged except for an increased hip frequency.

Another possibility to reduce the hip torques and still keep a high locomotion speed is addressed in Study 3 (Figures 11 and 12, see Video 1 at time 0:37). Here, starting from the solution of Study 2, we minimize the integral over time of the square of the hip torques and require the speed to be higher than 2 m/s. The resulting torques are lower than 300 Nm and the final walking speed still reaches approximately 2.5 m/s and is therefore higher than the required minimum speed of 2 m/s (which was passed after 10 s). The torque patterns indicate that both legs are operating in a symmetric manner again. However, the offset angle O has clearly increased, leading to an anterior position of the legs with respect to the body. Although it is a bouncing gait, the flight phases almost disappeared. This gait may be compared to human jogging at moderate speed. A gait sequence of this motion is given in Figure 13.

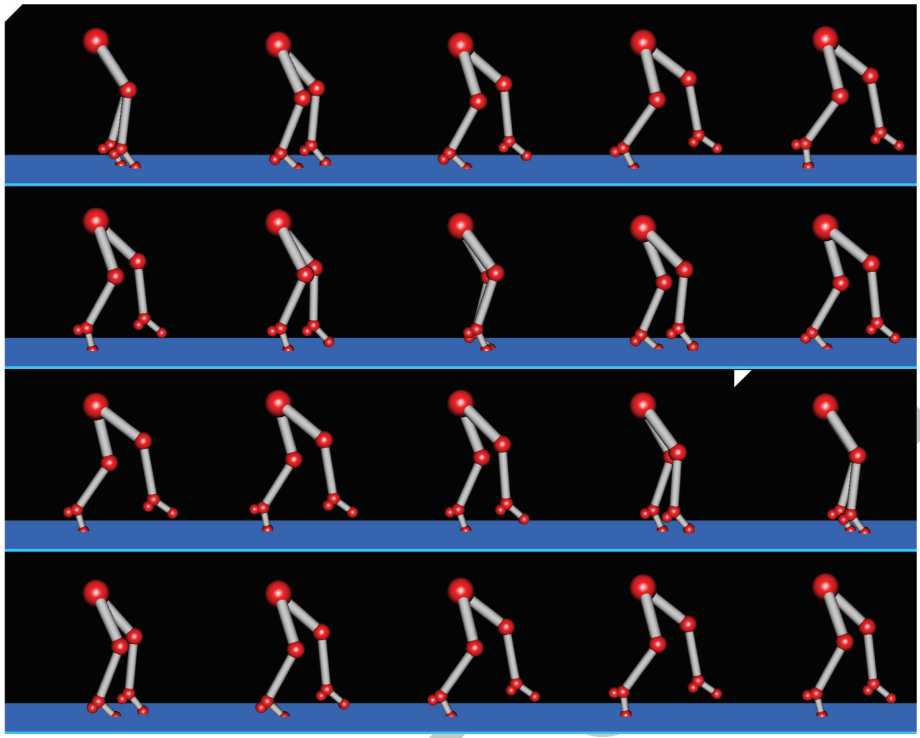

Fig. 13. Gait sequence with parameter set optimized for low hip torques and bounded velocity using the Nomad method (Study 3).

7. Conclusions and Outlook

In this paper a novel robot design was proposed to investigate the influence of compliant structures within the leg on the stabilization of human walking and running. In parallel, a simulation model was established and optimized for maximum speed and reduced hip torques. Both the experimental robot and simulation model predict stable walking and running patterns. To change from walking to running, in both situations an increase in step frequency is observed. Additionally, a change in the foot placement strategy is found: in walking the foot contacts the ground with the heel and rolls over to the ball whereas in running the foot is predicted to contact first at the ball (with no heel contact in the speed optimized simulation model). This was achieved by a more extended nominal configuration of the elastic structures spanning the ankle joint.

A strong limitation of the current approach is the fixed trunk orientation (pitch) with respect to the ground. Therefore, at running gaits the offset angle is shifted forward to avoid ground contact of the swing leg during protraction. By introducing an upper body we would expect an increased forward inclination of the body with higher running speeds. An efficient solution including sagittal trunk stability in walking based on a very simple neural network was shown by the RunBot humanoid biped (Geng et al. 2006). The neural network integrating sensors detecting knee and hip joint angles as well as foot contact sensors is calculating the activity of the motor neurons responsible for flexing or extending hip and knee.

On the other hand, we do not expect the human leg to be equally stiff during the stance and swing phase in running. This could well be achieved by using simple sensory feedback to enhance application of joint stiffness during the stance phase compared to swing phase. An interesting technical system which could adapt rotational stiffness and nominal angles of a joint based on the positions of two servo motors (the MACCEPA system (Van Ham et al. 2005)) was recently introduced by the Vrije Universiteit, Brussels.

The observed robot behavior and the predictions of the simulation model revealed many similarities and comparable limitations. This will help us to further enhance the system design with improved locomotor function and enhanced controllability relying on the underlying passive leg function. This approach could lead to novel strategies in motion planning where additional tasks (e.g. kicking a ball) might be integrated into a mechanically self-stabilized gait pattern. Moreover, the consideration of properties of engineered actuators (e.g. DC motors) in comparison to the behavior of muscle-tendon complexes might further give valuable insights in the organization and control of highly redundant movement tasks such as human locomotion. In a recent biped robot (Vanderborght et al.

2004), a novel pneumatic actuator was introduced to better represent the compliant function of muscles during humanoid walking. It remains for further research to evaluate the positive effects of such actuators on walking dynamics in comparison to human or animal locomotion.

Acknowledgment

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Appendix A. Index to multimedia extensions

Extension	Media type	Description
1	Video	Videos of different walking and jogging motions for Jena Walker and Jena Walker II (simulation and experiments)

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