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

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Abstract— **Elasticity in conventionally built walking robots is an undesired side-effect that is oppressed 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 elasticities and damping can sensibly be used in humanoid robots to improve walking capabilities. A modular robot system consisting of rigid segments, joint modules and adjustable elastic strings spanning one or more joints is used to configure a human-like biped. In parallel, a complex simulation model of the robot has been established. 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. Experiments on the real robot very well matched the numerical results. At higher speeds, transitions from walking to running are found in both the simulation as well as in the robot.**

Keywords— **locomotion, elastic legs, walking, running, control, optimization**

I. Introduction

THE control of human walking and running seems to be a rather challenging task. The musculoskeletal system consists of a many segments connected with joints of different degrees of freedoms and spanned by highly redundant muscle-tendon groups of different morphologies. Furthermore, many parts of the body are compliant or softly attached to the skeleton. With respect to the known approaches in control theory this seems to be an almost unsolvable task. This situation is getting 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.

An interesting way out of this unfortunate situation was demonstrated by the concept of passive dynamic walking of McGeer ([6]). He could build a purely mechanical bipedal robot which was able to walk down on a shallow slope without any actuation or sensory control. Based on this fascinating approach several walking robots with no or little sensory feedback were developed over the last decade ([3]). One drawback in all of these walking robots is the required complete knee extension during stance phase which limits the walking pattern to one preferred speed and step 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 well accepted that the leg behavior should be compliant and not stiff as suggested by the passive dynamic walkers ([2], [1]). This idea has been successfully demonstrated in the first hopping robots of Raibert and coworkers ([7]). Taking advantage of the passive 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 quite 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 ([4]) we found, that walking and running could well rely on the same 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 grounds or smaller obstacles.

A similar stabilizing effect can be found in 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. Therefore, it could may-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 ([5]) we were able to demonstrate passive 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 facilitate or even enable human 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 joints (cf. Figure 2). Second, a simulation model was implemented to identify appropriate leg designs and motor control parameters for stable locomotion.

II. 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, HRP-2, Johnnie or Qrio) 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 short flight phases have already been achieved for some humanoid robots in experiments (Qrio, Asimo), the performance is yet far from real jogging or running.

Elasticity in conventionally built articulated robots is considered an undesired side-effect that is being avoided as much as possible because it introduces high difficulties for an 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 and exhibits a very high degree of flexibility and stability of human locomotion which to a large extend is ensured by local properties of the musculoskeletal system and reflexes.

Fig. 1. The JenaWalker II bipedal robot testbed.

The overall target related to the work in this paper is to investigate how elasticities and damping can sensibly be used in humanoid robots to extend the range of locomotor capabilities as there is no humanoid robot design known yet which enables walking and real running with the same leg design. The goal is to put what reflexes and properties of the muscle-tendon complexes achieve for the stabilization of human locomotion into the mechanical structure of the robot in order to reduce the need for complex full feedback control algorithms. As a 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.

III. Mechanical Structure and Properties of the JenaWalker II Robot

A newly developed modular robot system (BioLEG-2; TETRA, Ilmenau) consisting of rigid segments, joint modules and adjustable elastic strings spanning hip, knee and ankle joints is used to configure a human-like biped (total robot mass: about 2kg). Each leg (hip height 45cm) consists of three segments including thigh, shank, and a prosthetic foot (SACH child foot, Otto Bock). Similar to the first biped robot (JenaWalker: Iida, 2006), 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 are spanning two joints leading to an inter-joint coupling within the leg. Furthermore, joint damping at the ankle joint is achieved by strings introducing friction between the moving parts of the joint. This damping is necessary to avoid vibrations of the foot during swing phase.

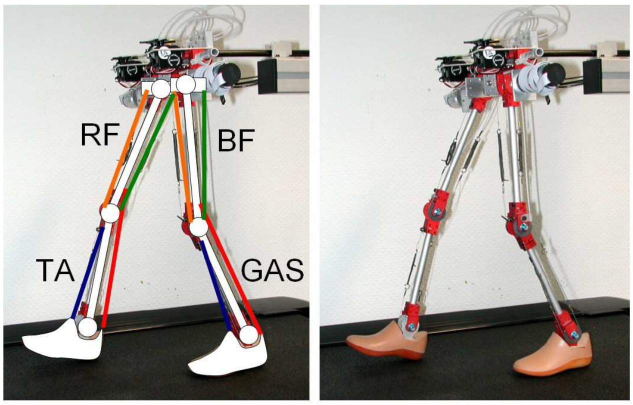

Fig. 2. The arrangement of elastic structures spanning the ankle, knee and hip joints.

Servo motors above the hip joints are used for tuning the rest lengths of the springs via Bowden cables (Figure 1). This represents shortening or extension of GAS, RF and BF resulting in postural adjustments of the knee and ankle joint. At the hip, sinusoidal oscillations (frequency f, amplitude A, offset angle O) are introduced by DC motors imitating the alternating activity of the hip joint muscles during locomotion. The compliance of the coupling between DC motor and hip joint is configurable and allows a joint play of about 10-15 degrees. This was identified to be useful to reduce impacts at the upper body and results in hip angle trajectories comparable to human walking and running ([9]).

It is important to realize, that this hip joint compliance can only be introduced if the leg itself is capable of stabilizing the gait pattern. The actual trajectory of the thigh with respect to the upper body can and does well deviate from the given sinusoidal pattern of the DC motor. Thus the hip motor does only determine the step frequency f and the approximate magnitude A of 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.

IV. Behavior of the Walking Robot

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

With increasing speed, the robot is able to adapt the leg movements when tuning the step frequency and the magnitude of hip oscillation correspondingly but without changing the adjustments of the elastic strings spanning hip, knee and ankle joint (Figure 3). At given speed, step frequency can be tuned by about a factor of about 2 by simultaneously adapting the magnitude of hip oscillation. Approximately at 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 cost of the magnitude 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 are acting together generating enough force to re-bounce the supported body even at flexed knee positions. This demonstrates the elastic leg behavior which can equally generate walking as well as jogging or bouncing gaits.

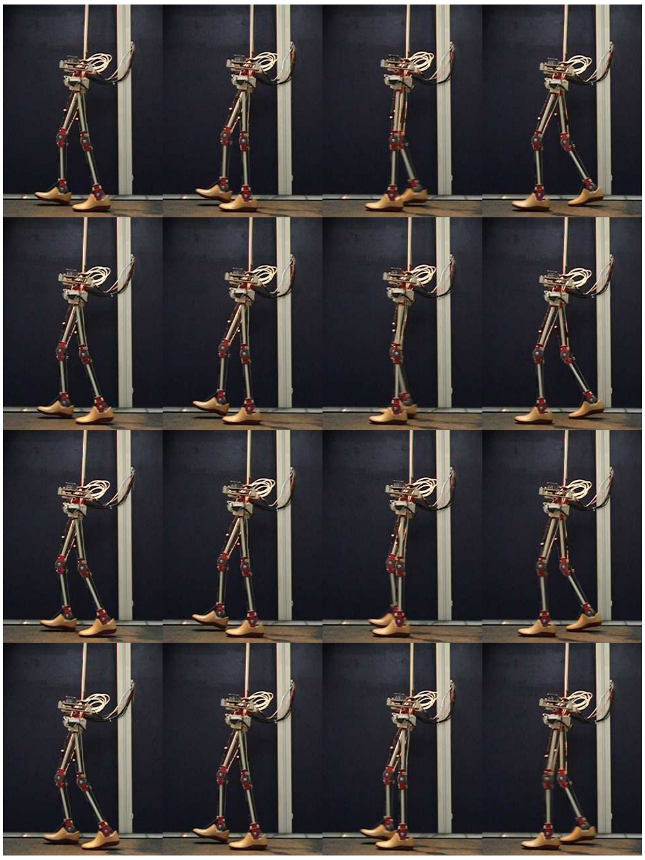

Fig. 3. Walking sequence of JenaWalker II robot at moderate speed.

V. Numerical Optimization of the Walking Motion

A complex 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 $m = 80kg$, leg length $l = 1m$) to allow further comparisions with experimental data. 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 ω_{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 rectus femoris and of the gastrocnemius springs have been optimized using robust numerical optimization methods based on (1) unconstraint implicit filtering [11] and (2) the Nomad method [10]. The latter method includes the ability to handle nonlinear constraints.

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

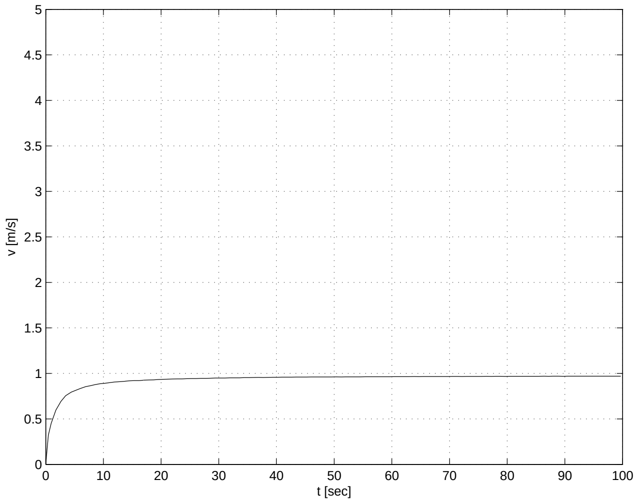

Fig. 4. Walking speed with initial parameter set.

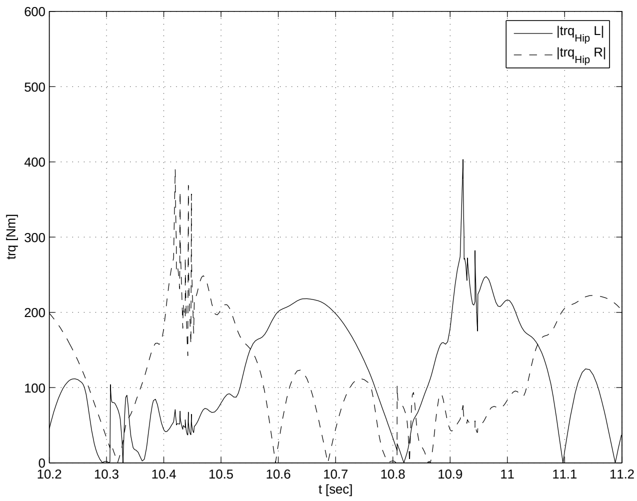

Fig. 5. Hip torques for walking motion with initial parameter set.

VI. Numerical Results

As a starting solution for the numerical optimization, a reasonable set of 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, the predicted speed of the robot converges to the final value. The hip torques are of comparatively high values and reach up to 400 Nm (Figure 5). The movement is symmetric between both legs with small sliding movements of the foot.

In the following, three optimization studies based on unconstraint implicit filtering (study 1) and based on Nomad method (studies 2 and 3) are presented.

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

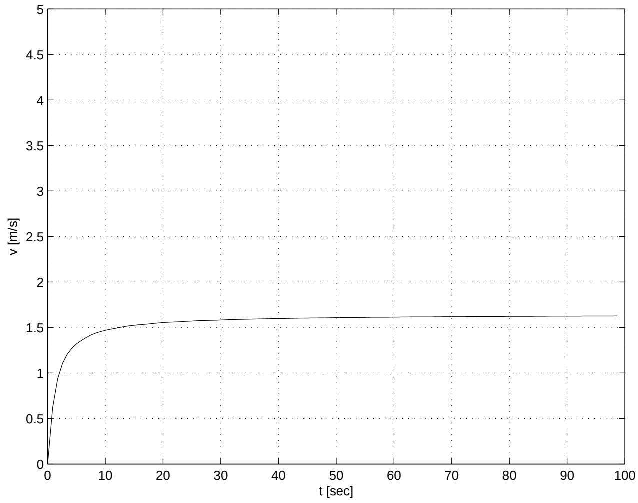

Fig. 6. Walking speed with parameter set optimized for speed using implicit filtering method (study 1).

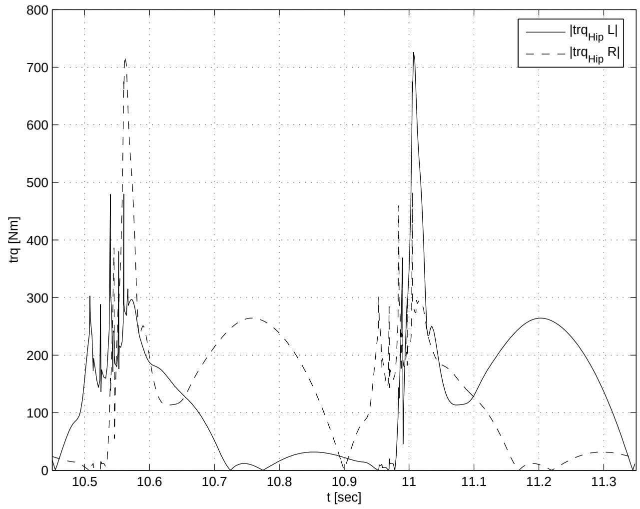

Fig. 7. Hip torques for walking motion with parameter set optimized for speed using implicit filtering method (study 1).

In study 2 (Figures 9 and 10), we address the issue of high hip torques by bounding these torques to be less than 500 Nm. The resulting walking motion obtained by Nomad method outperformes the result from study 1. The maximum speed predicted by the model is now 3.6 m/s taking advantage of flight phases. The function of the two legs are now asymmetric as indicated by the torque patterns (Figure 10).

In comparision to the solution in study 1, here the ankle joint is now stiffer with a more extended rest angle. Hence, foot contact occurs only at the ball and not anymore at the heel (in contrast to the observed movement in natural walking and in the JenaWalker II robot). At

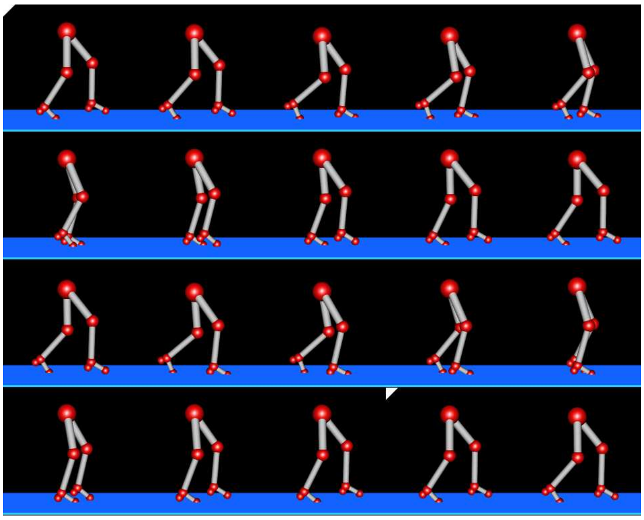

Fig. 8. Walking sequence with parameter set optimized for speed using implicit filtering method (study 1).

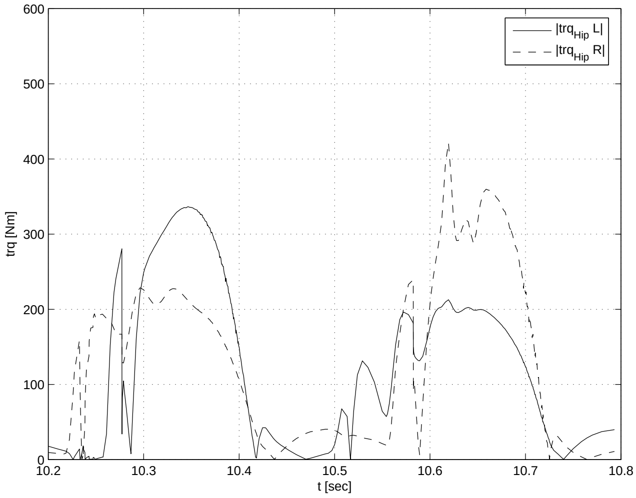

Fig. 10. Hip torques for gait pattern with parameter set optimized for speed and bounded torques using Nomad method (study 2).

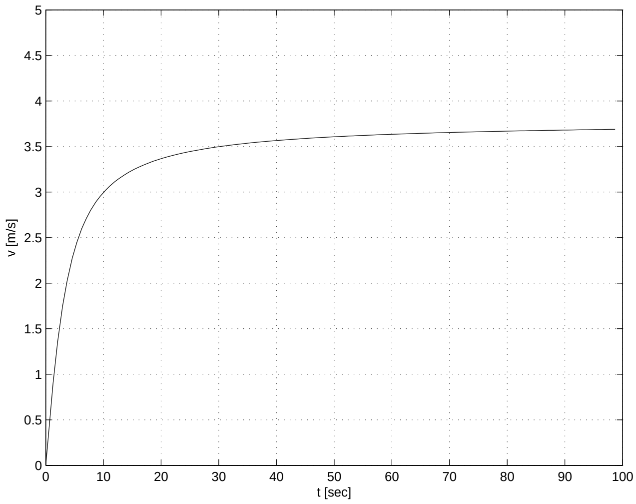

Fig. 9. Locomotion speed with parameter set optimized for speed and bounded torques using Nomad method (study 2).

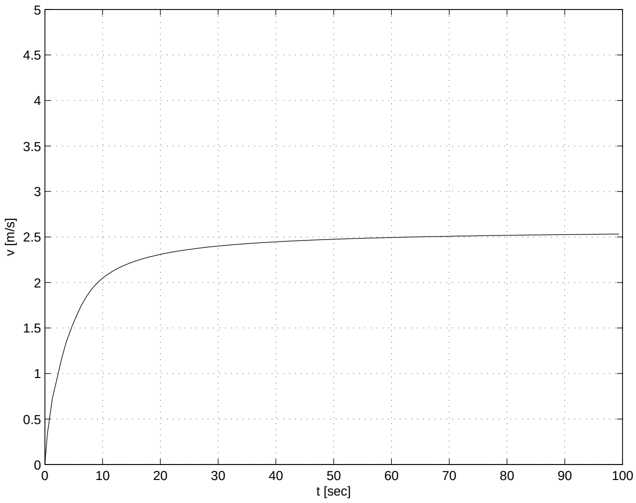

Fig. 11. Locomotion speed with parameter set optimized for low hip torques and bounded velocity using Nomad method (study 3).

the same time, the knee joint 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 step frequency.

Another possibility to reduce the hip torques and still keep a high locomotion speed is addressed in study 3 (Figures 11, 12). Here, starting from the solution of study 2, we optimize for minimum square of hip torques and bound the speed to be higher than 2 m/s. The resulting torques are lower than 300 Nm and the final walking speed is still at about 2.5 m/s and therefore higher than the bound speed of 2 m/s (which was passed after 10 seconds). The torque patterns indicate that both leg are operating in a symmetric manner again. However, the offset angle O has clearly increased leading to a anterior position of the legs with respect to the body. Although being a bouncing gait, the flight phases almost disappered. This gait may be compared to jogging at moderate speeds in humans. A gait sequence of this motion is given in Figure 13.

VII. 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 as well as the 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 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

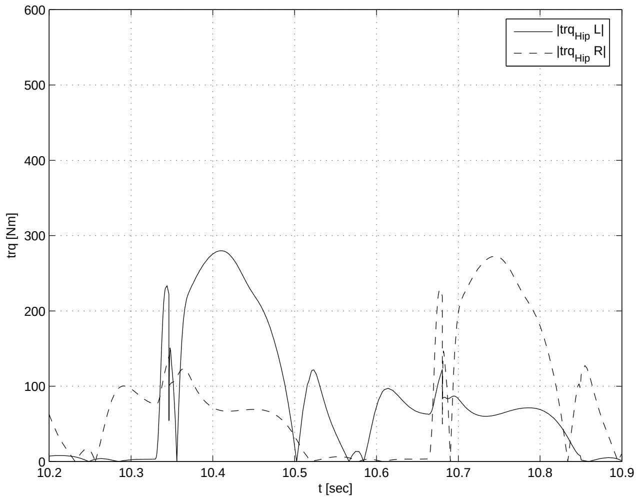

Fig. 12. Hip torques for gait pattern with parameter set optimized for low hip torques and bounded velocity using Nomad method (study 3).

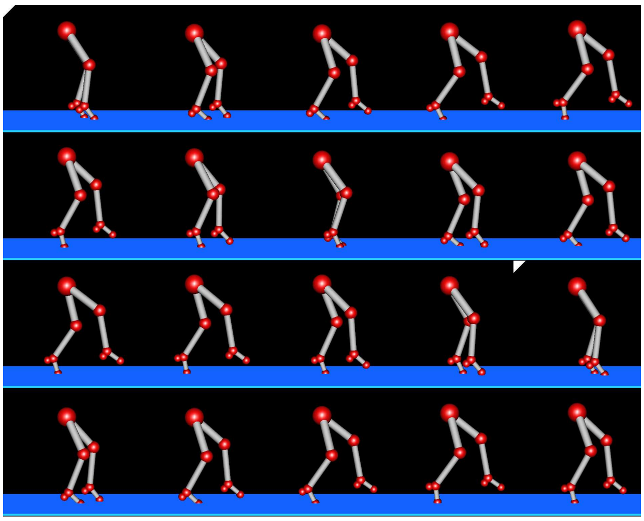

Fig. 13. Gait sequence with parameter set optimized for low hip torques and bounded velocity using Nomad method (study 3).

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 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 incline forward with higher running speeds. On the other hand, we do not expect the human leg to be equally stiff during stance and swing phase in running. This could be well represented by using simple sensory feedbacks to enhance joint stiffness during stance phase compared to swing phase.

The analysis of the behaviors of the robot and the simulation model revealed many similarities and comparable limitations. This will help us to a further enhancement 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. shooting a ball) might be integrated into a mechanically self-stabilized gait pattern. Moreover, the consideration of properties of technical 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 like human locomotion.

Acknowledgments

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