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CONCEPT AND DESIGN OF THE BIOBIPED1 ROBOT FOR HUMAN-LIKE WALKING AND RUNNING

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Biomechanics research shows that the ability of the human locomotor system depends on the functionality of a highly compliant motor system that enables a variety of different motions (like walking and running) and control paradigms (like flexible combination of feedforward and feedback control strategies) and reliance on stabilizing properties of compliant gaits. As a new approach of transferring this knowledge into a humanoid robot, the design and implementation of the first of a planned series of biologically inspired, compliant, musculoskeletal robots is presented in this paper. Its three-segmented legs are actuated by compliant mono- and biarticular structures, that mimic the main nine human leg muscle groups, by applying series elastic actuation consisting of cables and springs in combination with electrical actuators. By means of this platform, we aim to transfer versatile human locomotion abilities, namely running and later on walking, into one humanoid robot design. First experimental results for passive rebound, as well as push-off with active knee and ankle joints, and synchronous and alternate hopping are described and discussed. BioBiped1 will serve for further evaluation of the validity of biomechanical concepts for humanoid locomotion.

Keywords: hopping; running; jogging; walking; biped; biomechanics; humanoid locomotion; compliance; mechanical elasticity; series elastic actuation

1. Background

Walking, running, and hopping appear as natural and quite easy tasks for a healthy human, yet for today's robots they impose big challenges. There are various problems for robots to perform these kinds of motion, including, but not limited to, mechanical robustness and achievable performance due to high joint torques, constraint forces and shocks from impacts, a high peak power demand especially in hopping and running, and, of course, gait stability of the robot in different gaits.

The direct transfer of methods from control engineering, originating in motion control of robot arms, to legged robots that have to perform in the real world has not yet resulted in human-like robot locomotion. Most existing humanoid walking robots are either fully actuated, rigid and rely on ZMP-based control schemes[1] or are underactuated and exhibit only a quite limited motion repertoire with quite limited versatility and robustness.

ZMP-based robots comprise machines such as ASIMO,[2] HRP[3] or Johnnie.[4] Their design is based on the principle of serial kinematic chains of rigid (rotary) joints and links with usually six or seven fully actuated and feedback-controlled joints per leg. Actuated by stiff, rotary motors, the joints are controlled to track desired motion trajectories by using independent joint space controllers that are based on either single-joint or multi-joint models. Although these robots can reliably perform a variety of stable walking motions, their locomotion still lacks the sleekness and performance that can be observed in human jogging and running gaits. Such robots cannot exploit natural dynamics and self-stability[5] of compliant and elastic, dynamic human locomotion.

Highly underactuated passive dynamic walkers[6] were pioneered by McGeer, who introduced the concept of natural cyclic behavior for a class of relatively simple bipedal systems, i.e., consisting of two-segmented legs displaying a compass-like gait on an inclined plane. Stable walking is enabled by the appropriate balance between injection of energy due to the slope and loss at impacts. The principles of passive dynamic walkers have been used to develop powered bipeds that walk with high efficiency in a more human-like way than the predecessors by exploiting natural dynamics.[7] The gaits of these walking machines, however, are characterized by narrow stability regions and weak robustness. Furthermore, almost all them are lacking an actuated foot joint (as they do not need an ankle joint) and can only walk at a specific speed and can neither jog, nor walk up stairs or stand still.

Raibert[8] developed a number of single- and multi-legged hopping machines, realized by compliant telescopic legs. This approach was later formalized with the spring-loaded inverted pendulum model, which was also used to describe human-like bouncy gaits.[9] Raibert's original bipedal robots demonstrated a variety of dynamically stable gaits, but could not stand still. Moreover, the design of the leg was very simple and lacked the segmentation found in the human leg. This issue was addressed in the recently presented bipedal robot Petman[10] where the focus lies on the advancement of sophisticated controllers, according to the so far commonly available information. However, it integrates mechanical elasticities only to a small extent in the knee and ankle joints and is hydraulically actuated, as the quadruped BigDog.[11]

From this short excursion into the state-of-the-art in bipedal robots, it can be summarized that, whereas conventionally designed robots lack human-like performance in terms of self-stability, energy-efficiency and locomotion performance (e.g. speed and endurance), passive dynamic walkers can only exhibit one or two behavior patterns, and exhibit only a limited adaptability against environmental variations. Furthermore, only very few robots are targeted at the exploration and investigation of biomechanical aspects that are important for the realization of human-like motion performance and capabilities. Here, only few research projects are known, such as the pneumatically driven jumping monopod of Hosoda et al.,[12] who studied the role of human-like, series elastic structures built in the monopod's leg. A further recently published work involves the biped Athlete, which was developed by Niyama et al.[13] The robot has two-segmented legs and is capable of performing a few

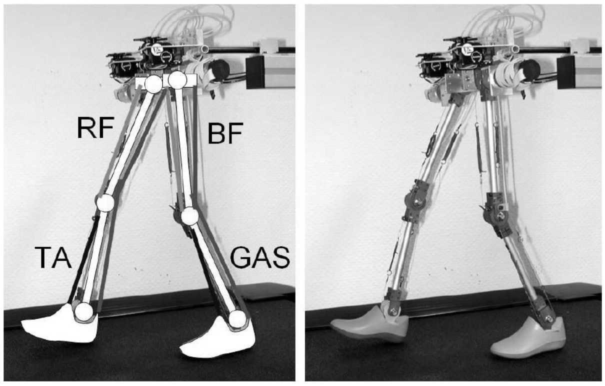


Fig. 1: Three-segmented, highly underactuated, elastic legs of JenaWalker II[14] with passively integrated mono- and biarticular structures, marked on the left-hand side: *Rectus Femoris* (RF), *Biceps Femoris* (BF), *Gastrocnemius* (GAS) and *Tibialis Anterior* (TA).

running steps based on activation patterns for the pneumatic actuators derived from human EMG data.

The project and robot presented in this paper are based on the previous developed JenaWalker II, which is an elastic and biologically inspired bipedal walking machine that is attached at the trunk to a lateral guide (cf. Fig. 1). Each three-segmented leg is actuated by one motor only (which makes it a highly underactuated robot) and the joint coordination is achieved with series elastic structures. Nevertheless, it is, to the authors' best knowledge, the first robot model that exhibits in simulation and experiment the realization of different gaits with the same kinematic leg design and the same type of controller.[14] These results are coherent with the observation of biomechanics researchers that a bipedal spring-mass template model can reproduce, aside from the compliant stance-leg behavior found in running, also the stance dynamics observed in walking.[15] For a long time, bipedal walking and running had been investigated using different, conceptual models, the former by an inverted pendulum model[16,17] and the latter by a spring-mass model.[9] It was shown, however, that vaulting over stiff legs cannot reproduce the mechanics of human walking.[18] Recent biomechanical studies revealed, that the fundamental gaits of walking and running are much less different than generally assumed in robotics and that elastic legs are crucial for both bipedal running and walking.[15] With JenaWalker II it was demonstrated that human-like behavioral diversity can be achieved even by a relatively simple control scheme if the robot's actuation design considers morphological properties of the human leg. It should be noted that the motion control can be largely facilitated by the intrinsic dynamics of a segmented body which has been tuned by carefully designed elastic structures spanning the joints (see Fig. 1). These results support our hypothesis that biomechanical findings concerning human locomotion are essential in order to realize humanoid robots with really human-like locomotion capabilities.

In the next section we will introduce the goals of the BioBiped project and the intended investigations with BioBiped1. Section 3 presents the core concepts and main characteristics of BioBiped1, while Section 4 describes its technical realization and features. Section 5 focuses on the results obtained from experiments regarding the robot elastic leg operation and hopping motions. Finally, we summarize the paper and describe future work.

2. Goals of the BioBiped Project and Robot BioBiped1

The BioBiped project aims at the longterm realization of human-like three-dimensional (3D) stable running, walking and standing in a humanoid robot and herewith allowing the free selection of speed and gait. One characteristic of this project is that the application of biomechanical insights is not only considered as an important part, but is the very basis for the design of each robot prototype developed within the project. With the BioBiped project, we intend to investigate if human-like hopping, running and walking can be achieved in one robot design using non-conventional actuation concepts derived from biomechanical knowledge. The approach investigated in this project is based on an iterative development and experimental evaluation of new concepts of bio-inspired humanoid robots in close interaction with the development and application of conceptual as well as physically detailed simulation models for their motion dynamics. The simulations models are motivated from findings from human gait analysis and experiments.

The *BioBiped1* robot described in this paper is the first of a series of robots with successively enhanced designs and capabilities. Its goal is to prove by experiment that jogging can be achieved in principle using an elastic, musculoskeletal, three-segmented leg structure. The leg design approximates structure and function of the main nine human leg muscle groups and serves as proof-of-concept for jogging ability. Each leg has four joints, three in the sagittal plane (hip, knee and ankle pitch) and a fourth hip roll joint for lateral leg placement. The upper body consists of a constant mass. Its motions are restricted during first experiments for proof-of-concept to a one-dimensional vertical motion and will possibly be extended to the saggital plane. The goal of a revised version of the robot will be to demonstrate jogging in the sagittal plane. For this purpose, the robot will be placed on a treadmill and its upper body motion will be constrained to the sagittal plane. The robot's hardware will be based on a refined version of BioBiped1 taking into account the experimental results for improvements of the mechanics and electronics.

The aim of the following robot version will be to demonstrate jogging, walking and standing in the sagittal plane. Variations in the foot design will be studied to enable heel-toe walking and fore-foot jogging motions. Additional actuation and mass will also be considered in the trunk to move the upper body to support jogging and walking gaits. The goal of the final robot version will be to demonstrate jogging, walking and standing without external aids for postural stability. To enable stable 3D robot motion the addition of an actuated degree of freedom in the ankle (roll motion) will be evaluated. Furthermore, the extension of the trunk with arms will be considered to improve postural stability and locomotion efficiency by contra-lateral arm motion.

The choice to start with the investigation of bouncy gaits for BioBiped1 is motivated by biomechanical findings. These indicate that, although human-like walking is mechanically less demanding than running, it is more complicated to represent with simple biomechanical models and to control. The locomotor function of BioBiped1 will be realized and evaluated in the following separate consecutive stages:

(1) The leg repulsive function (leg compression/extension during stance), which regards mainly the capability to generate sufficient repulsive leg forces during stance phase to achieve clear flight phases;
(2) The leg propulsive function (for- and back-swinging of the leg), which addresses the issues of fast and precise swing motions of the leg with sufficient ground clearance and propulsion during the stance phase;
(3) The cyclic stability in the sagittal plane (2D hopping), which requires the adaptation of the leg functions for postural stability.

An advantage of this step-by-step approach is, that weaknesses of the robot's design can be identified at an early stage and, thus, can be taken into account in further versions of the robot.

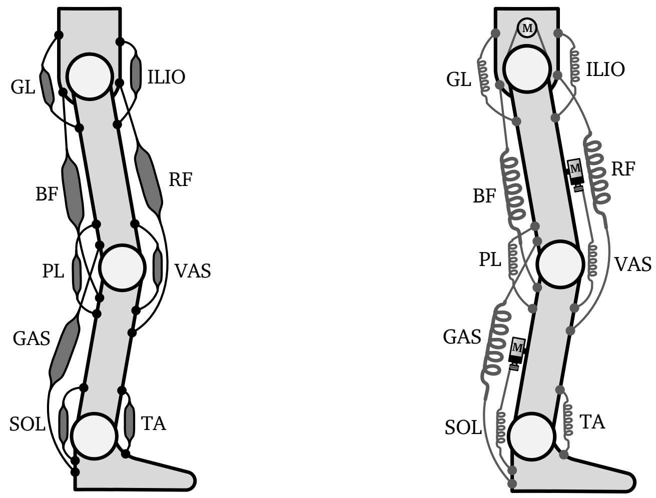
Following this approach, the focus of the experiments described in this paper is placed on investigations regarding the repulsive leg function. The motion of the robot is limited to a single vertical degree of freedom, hence resulting in the realization of hopping gaits. In particular, the ability of the robot to rebound (passively) and to generate (actively) enough thrust to induce continuous hopping motions is investigated (as described in Section 5).

3. Concept and Key Properties of BioBiped1

In order to transfer biomechanical concepts and insights from human locomotion to a robot and to investigate and evaluate these concepts using that platform, it is crucial to implement the main functional properties of the human leg in the robot. A key idea behind the design of the robot is that the motion patterns should mainly result from or highly be facilitated by the mechanical properties of the robot, which is likely to improve energy efficiency and robustness. These requirements call for a design that reproduces at least to some extent the mechanical and morphological features of the human leg.

A fundamental design feature of the human leg is segmentation. Accordingly, the robot leg is composed of three segments (thigh, shank, and foot) and four joints (along the pitch axis at the hip, knee, and ankle, and along the roll axis only at the hip, see Fig. 3). The joints along the pitch axis are used for the operation of the leg in the sagittal plane, while the hip roll joint will allow for lateral leg placement to stabilize 3D locomotion at a later stage. The robot is also provided with a torso connected with the pelvis by one joint, so that the trunk can be leaned for- or backwards.

Another main characteristic of the robot is the implementation of elastic leg behavior, which distinguishes it from conventional humanoid robots. Biomechanical models suggest that compliant leg behavior is the mechanical basis of bouncy gaits like running and can also enable walking gaits.[5,9,15] Also, the dynamics of the center of mass (COM) and the resulting pattern of the ground reaction force (GRF) during human locomotion can be explained based on compliant leg function.[15] Therefore, it is focussed on the realization of compliance in the legs of BioBiped1, which is achieved by actively and passively integrated



(a) (b)

Fig. 2: The nine main muscle-tendon groups of the three-segmented human leg (a) are mimicked by series elastic cable-spring structures in the BioBiped1 robot, where the monoarticular structures are selected as active ones (b).

elastic, mono- and biarticular structures, as depicted in Fig. 2b. The structures represent the main muscle groups of the human leg (cf. Fig. 2a). The structures *Rectus Femoris* (RF), *Biceps Femoris* (BF) and *Gastrocnemius* (GAS), each spanning two joints, represent biarticular muscles. The group of monoarticular structures, spanning one joint, consist of the muscle pairs in ankle, knee, and hip joint: *Tibialis Anterior* (TA) - *Soleus* (SOL), *Popliteus* (PL) - *Vastus* (VAS), and *Gluteus Maximus* (GL) - *Iliopsoas* (ILIO).

As shown in Fig. 2b, all biarticular structures are integrated passively in the legs of BioBiped1. Active actuation is incorporated for the monoarticular extensors of each knee and ankle muscle pair, VAS and SOL. The corresponding flexors, PL and TA, and the muscle pair GL-ILIO in the hip are passively implemented. This configuration is motivated by insights from biomechanics that power generation is mainly achieved by monoarticular muscles, while biarticular muscles mostly contribute to transfer force/energy between joints.[19–21] Depending on the current investigation, the passive structures can be attached and removed as required (cf. Section 5).

4. Technical Realization

4.1. *General data*

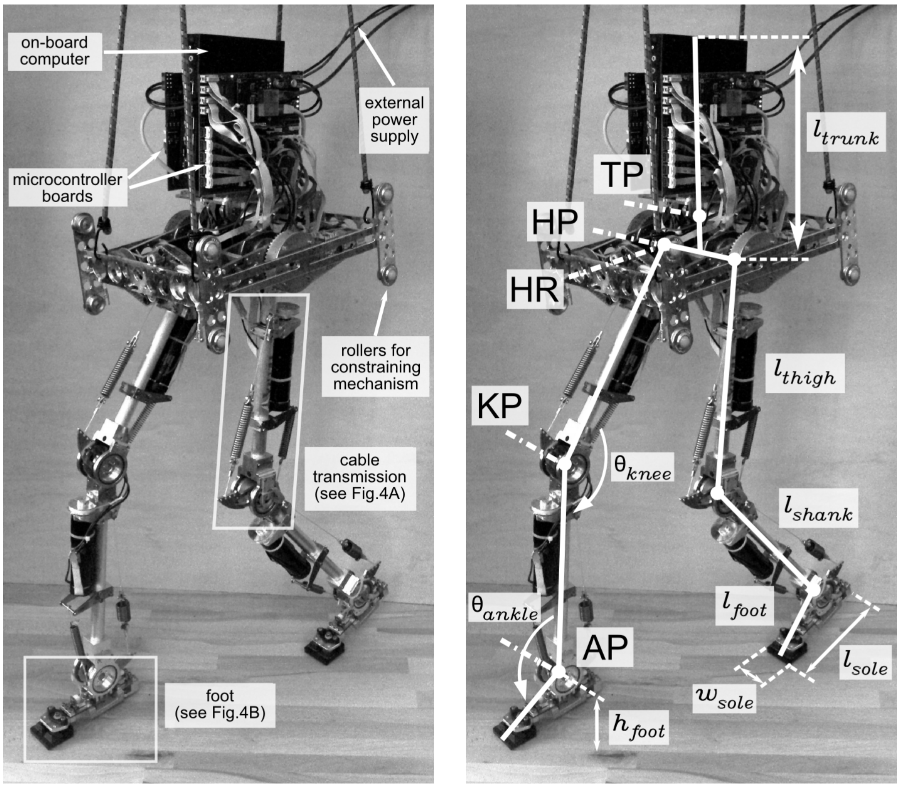
The hardware and mechatronics of the BioBiped1 robot has been developed in cooperation with TETRA GmbH, Ilmenau. Its main characteristics are indicated in Fig. 3. The robot leg morphology is based on human properties, i.e., the lengths of the segments are chosen to have the same ratios as in average human adults. On the other hand, less attention was yet dedicated to the trunk, which is comparatively less extended and lighter than in humans. As a result, the overall center of mass (CoM) of the robot is located under the hip joint. Although this has only minor influence for the current experiments (i.e. hopping motions constrained to 1D), subsequent robot versions will include a trunk with more human-like properties resulting also in a higher CoM.

The robot is equipped with proprioceptive (encoders for motor and joint positions, see Fig.4A&C) and exteroceptive sensors (force sensors in the foot, shown in Fig.4B, and inertial measurement unit including gyros and accelerometers). The sensors serve for two main purposes, first, to enable detailed monitoring of the robot's experimental performance and, second, to allow the investigation of a number of different feedback and feedforward control schemes for walking and jogging. The robot carries its control hardware (microcontroller boards and computer) and can operate autonomously, except for its power supply as it is planned to add batteries at a later stage of development. As communication bus EtherCAT has been chosen which enables high bandwidth and low latencies. By this, true multi-variable control is enabled for the robot and frequencies of more than 10 kHz can in principle be achieved for the robot.

4.2. *Actuation of the leg joints*

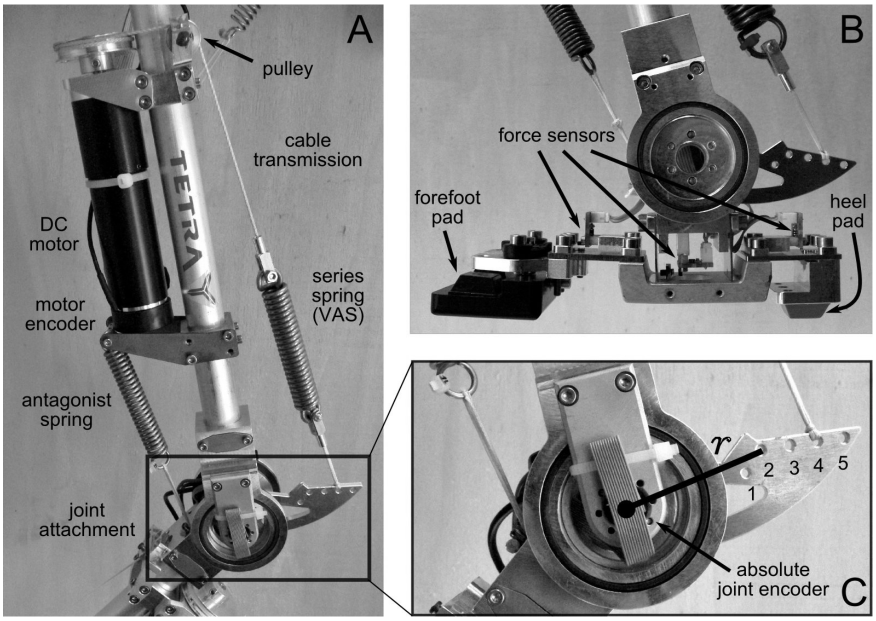
As mentioned in Section 3, a combination of passive and active structures is integrated in the legs of BioBiped1 to mimic the function of the muscle-tendon structures present in the human leg (Fig. 2a). The passive structures (approximating GAS, RF, BF, TA, PL, GL, ILIO muscle functions) are implemented using extension springs connected via cables to the appropriate robot segments. The remaining two active monoarticular structures (VAS, SOL) are actuated by geared rotary electric direct-current (DC) motors, which were selected due to their compact size, ease of utilization and high-bandwidth control. In both knee and ankle joint, the motor is connected to the joint using, similar to the passive structures, a cable including an extension spring. The length of the cable is adjusted by the motor by winding the cable around the pulley attached to the motor axle (see Fig. 4A). As shown in Fig. 4C, the cable can be attached on the joint side with various lever arms (from 1 to 5). As the transmission is unilateral, the actuation principle is slightly different from the original bidirectional Series Elastic Actuator (SEA),[24] where the gearbox is connected by a rotational spring to the joint. Furthermore, the original SEA concept introduces elasticity directly in the joint. At the hip's pitch and roll joints, the motors are connected to the joints bilaterally via a timing belt transmission to allow for precise, high-bandwidth control of the leg's angular position.

For the sake of simplicity, the stiffness of the series elastic elements is constant and not adjustable. However, even in such case, the stiffness at the joint level can be modulated by the actuator in series or by changing the lever arm of the joint. In addition, the leg configuration can be used to adjust to the apparent overall stiffness of the leg (for example, an extended leg will appear stiffer than a bent leg for equal joint stiffness values). With these strategies, the overall leg stiffness can be adapted to some extent to match the requirements depending on the conditions (such as the gait and the speed).



Dimensions and masses	
Segment lengths	l_{trunk} = 269 mm; l_{thigh} = 330 mm; l_{shank} = 330 mm ; l_{foot} = 122 mm
Foot dimensions	h_{foot} = 67 mm; l_{sole} = 168 mm; w_{sole} = 40 mm
Leg length	$\sim$ 0.7 m (from hip to sole with extended leg)
Total mass	$\sim$ 9.2 kg (the CoM is located at $\sim$ 0.13 m under the hip joint)
Actuation	
Motors	AP, KP, HP, HR: Maxon RE30 60W (66:1); TP: Maxon RE16 4.5W (84:1)
Transmissions	AP, KP : unilateral compliant (wire with series spring) ; HP, HR, TP: bilateral rigid
Stiffnesses	AP, KP: variable according the experiment, see Table 1
Sensors	
IMU	ADIS 16364 with 6 axes (angular speed: 3 axes; linear acceleration: 3 axes)
Encoders	incremental for motor position (all joints), absolute for joint position (AP, KP, HP, HR)
Force sensors	custom-made, 3 axes per foot (parallel to the sole for the whole foot and normal to the sole for the forefoot and the heel pads)
Control system	
Hardware	2 custom-made microcontroller boards and an on-board control computer communicating via EtherCAT bus
Software	Orocos Real-Time Toolkit[22] and Robot Operating System (ROS)[23]

Fig. 3: Main characteristics of the BioBiped1 robot. TP, HR, HP, KP, AP refer to trunk pitch, hip roll, hip pitch, knee pitch and ankle pitch, respectively. Close-ups of the active cable transmission at the knee and of the foot design are given in Fig. 4A and B, respectively.



Attachment point	1	2	3	4	5
r [mm]	36.4	43.0	50.8	58.7	66.5

Fig. 4: Close-ups of the main mechanical features of the robot. **A**: Cable transmission at the knee joint mimicking the human muscle VAS. **C**: Lever arms in knee and ankle joint can be adjusted (from 1 to 5). Distance of the attachment points from knee/ankle joint axis are given in the table below the close-ups. **B**: The foot is equipped with 3 forces sensors, which measure the force parallel to the sole and the forces normal to the sole at the front (i.e. on the forefoot pad) and the back (on the heel pad), respectively.

4.2.1. *Dimensioning of the actuators*

In the first phase of development of BioBiped1, a motor-gear unit selection was carried out based on multibody system dynamics model and simulation of BioBiped1, incorporating series elastic actuator models and a realistic foot-ground contact model.[25,26] We investigated the actuation requirements for slow human running data ($\sim 2\,\text{m/s}$) and computer generated hopping motion. The human running data were given as joint angle trajectories obtained from human experiments using an instrumented treadmill with force sensors and a camera system, consisting of eight high speed infrared cameras.[27]

An inverse step-by-step approach was applied to compute the corresponding actuation requirements based on the rigid body dynamics of BioBiped1 for the desired motions.[26] The analyses yielded motor-gear units with the specification of the Maxon RE30 motor (60 W, 24 V) and planetary reduction gearbox GP 32C with gear ratio 66:1. Preventively, a reduction of 10% of the level of efficiency (i.e. RPM) was included in the calculations. This combination is used for all leg joints.

Although known from humans, that not all joints require the same power, here we chose on purpose the same actuators for all joints, since the analyses carried out indicated both high velocities and torques for all joints during almost the entire simulation time of several cycles. Also, with BioBiped1 being the first prototype in a series still many questions are open, especially the role of the passive, series-elastic structures in terms of power reduction. Therefore, in order not to overcomplicate the first robot version and not to delay access to insights from robot experiments, we decided to have all leg joints driven by the same powerful actuators in BioBiped1 with the possibility for refinement in later versions.

4.2.2. *Selection of the springs*

For the estimation of the spring characteristics, we used human experiment data regarding the joint angular stiffnesses c and maximum angular deflections $\Delta\theta_{max}$ during (1) hopping at preferred height[28] and (2) running at moderate speed (~ 2 m/s).[27] The data were scaled down to the robot weight and leg length conserving the ratios of kinematic data. The data from humans are expressed using the total body weight and the leg length. To apply to the robot, the robot weight (90N) and leg length (0.7m) are used. The equivalent linear stiffnesses k and maximum deflections Δl_{max} were then computed for each available attachment point on the joint side (see Fig. 4.C) as follows:

$$k = \frac{c\,\Delta\theta_{max}}{d_{max}\,\Delta l_{max}}. \tag{1}$$

where d_{max} is the value of the lever arm of the spring force with respect to the joint at the maximum joint angular deflection. This allowed us to define appropriate ranges for the spring stiffnesses (i.e. $k \in$ [5,20] N/mm) and corresponding elongations ($\Delta l_{max} \in$ [10,35] mm). The springs actually used in the experiments were then selected by trial and error from a set of springs satisfying these characteristics.

5. Experimental Results

In this section, the results of the first experiments performed with BioBiped1 are presented. The initial angles and the spring setup for the knee and ankle joints in each experiment are given in Table 1. Videos of the synchronous and alternate hopping experiments (Sct. 5.3 & 5.4) are provided on the project's website `http://www.biobiped.de`.

5.1. *Passive rebound*

First, the ability of the robot to rebound passively is assessed and the restitution of the legs is estimated. For this purpose the robot was dropped from a given height and its motion was recorded with a high-speed camera (cf. Fig. 5). Motors were PD-controlled to constantly keep their initial positions. The total ground reaction forces were additionally measured with a Kistler force plate. The vertical forces are depicted in Fig. 6.

By trial and error adjustment of the properties of the ankle and knee extensors, SOL and VAS, and the passive biarticular muscle GAS, the robot was able to rebound as much

Experiment	joint	initial angle [deg]	muscle	stiffness [N/mm]	attachment [number]	passive antagonist
Passive Rebound	ankle	140	Sol	6.7	3	rope
			Gas	4.1	5	-
	knee	155	Vas	7.9	5	rope
Active Push-Off	ankle	95	Sol	7.9	3	rope
			Gas	4.1	1	-
	knee	125	Vas	15.5	3	rope
Synchronous Hopping	ankle	115	Sol	13	2	spring
	knee	120	Vas	15.5	2	spring
Alternate Hopping	ankle	115	Sol	13	4	spring
	knee	120	Vas	15.5	4	spring

Table 1: Initial joint angles and spring setup in the experiments. The zero position of the joints corresponds to a completely folded and 180 deg in all joints correspond to a fully extended leg.

as 5 cm, when dropped from a height of approximatively 15 cm (Fig. 5). The flight phase lasted for about 150 ms and was followed by smaller bounces (cf. Fig. 6). These were however difficult to qualify because postural control was not implemented at that stage and, past the second stance phase, the robot had sometimes to be supported in order not to fall.

This experiment confirmed that the robot is able to achieve a good energy restitution ratio passively. Moreover, sources of energy losses, such as the large impact at landing (see Fig. 6) and vibration of the spring-cable structures perpendicular to their long axis were identified. This effect injects energy in this oscillating movement rather than in the extension of the springs. Also, the oscillation of the mass of the springs causes an oscillating joint torque pattern. Hence, implementing measures to reduce their influence, in conjunction with the optimization of the spring properties, could further improve the robot's performance.

5.2. *Push-off with active knee and ankle extensors*

In the next experiment, a strong push-off movement was induced, starting from an initial crouched position, by powering the knee and ankle actuators at the nominal voltage (24 V), resulting in a fast straightening motion of the legs. As for the passive rebound experiment of Sect. 5.1, the motion of the robot was not rigidly constrained and without any support, the robot would be falling backward or forward. Therefore the robot was hold by ropes to prevent this and to keep the pelvis directly above the foot contact point.

The vertical ground reaction force data (shown in Fig. 7) showed a clear flight phase of approximately 80 ms, starting just before 0.4 s. This demonstrated that the robot was able to generate enough thrust to lift off by itself from the ground, a prerequisite for the initiation of hopping which was then considered in the two subsequent experiments.

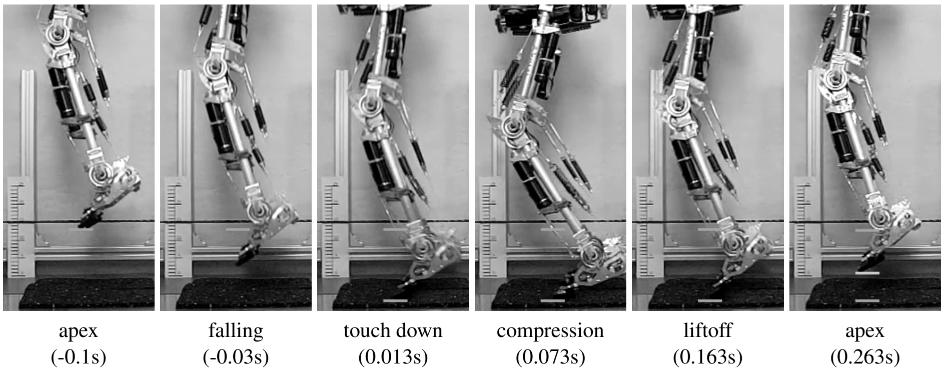


Fig. 5: Passive rebound from 15 cm drop (timestamps correspond to Fig. 6).

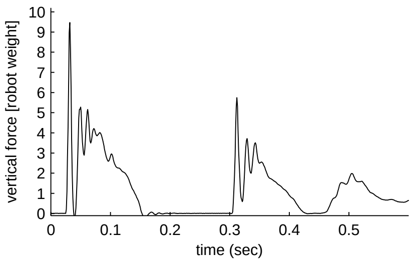


Fig. 6: Total vertical ground reaction forces during the passive rebound, depicted in Fig. 5, measured by a force plate and normalized to BioBiped1's weight.

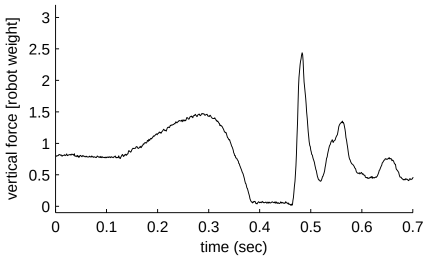


Fig. 7: Total vertical ground reaction forces during push-off with active knee and ankle extensors, measured by a force plate and normalized to BioBiped1's weight.

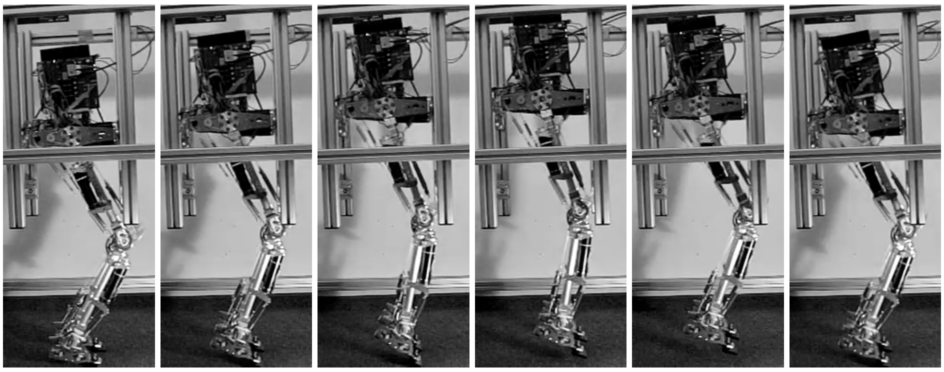
5.3. *Synchronous hopping with feedforward control*

After the passive rebound and the active push-off were both successful, hopping motion with synchronous operation of the legs (synchronous hopping) was investigated. For this purpose, the motion of the robot was constrained to vertical trunk movements (see Fig.8). The constraining mechanism, attached as an add-on to the pelvis of the robot, was equipped with four sets of rollers sliding with low friction in vertical guides.

To achieve the hopping motion, a relatively simple feedforward control scheme was implemented for the control of the knee and ankle joints. The knee and ankle motors were PD controlled to follow reference positions switched periodically between two set points (see Fig.9a-top). These corresponded respectively to configurations with bent (knee and ankle flexed) and extended (knee and ankle straightened) legs. The angle range was approximately 30 ° for the knee joint and 25 ° for the ankle joint. The durations of the extension and the bending phase were set to 200 ms and 160 ms respectively.

The same strategy could have been applied to the control of the hip joint as well, but the nature of the constraining mechanism required to reduce the constraining forces. Hence, the hip pitch motor was instead controlled to follow the hip pitch angle position, resulting in a nearly passive motion of the hip. The joint position was then stabilized by antagonist springs mimicking the coactivation of the GL and ILIO muscles of Fig.2a.

Although the motion showed considerable variation (which is not surprising when considering the feedforward character of the control), synchronous hopping could be generated and the robot was able to perform more than 30 hopping cycles continuously before it was stopped by the operator. Flight phase durations as long as 200 ms (see ground contact force measurements in Fig. 9a) and ground clearance of up to 5 cm (see Fig. 8 and the corresponding video) could be achieved. The average duty factor observed in the synchronous hopping experiment was 0.47, i.e. the ground contact time of the feet during hopping was on average 47 % of the total time of the hopping motion.

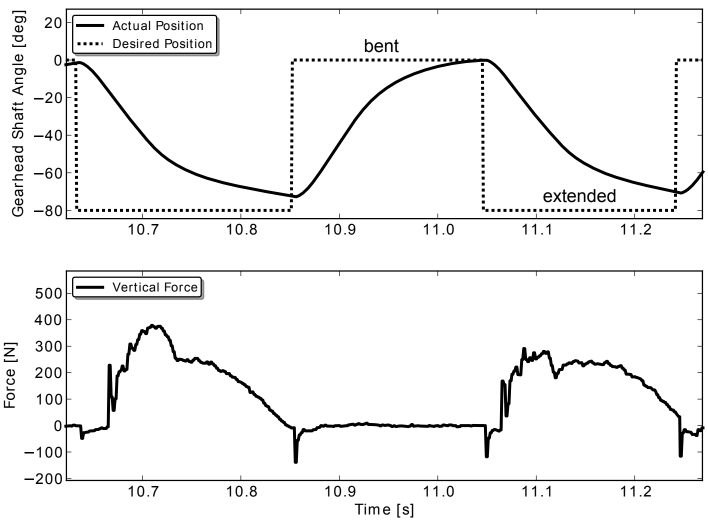


Max. Compression | Stretching | Lift-Off | Apex | Flexion | Touch-Down

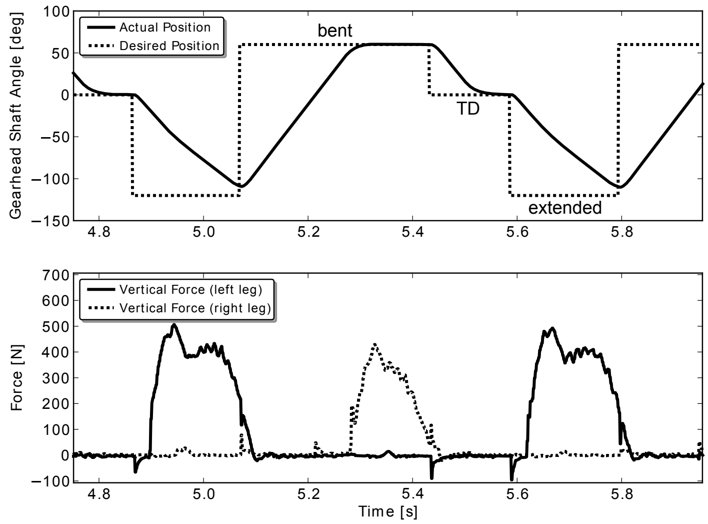
Fig. 8: Snapshots of one cycle of synchronous hopping motion with feedforward control. The robot pelvis motion is constrained to a 1D vertical translational degree of freedom by the surrounding frame.

5.4. *Alternate hopping with feedforward control*

Upon completion of the synchronous hopping experiment, the realization of a hopping motion where the legs are supporting the body alternately (alternate hopping) was considered. This task is highly relevant for testing the performance of the robot because the loading condition for each leg is close to that in running gait. The same experimental setup as for the synchronous hopping experiment was used. The lever arms at the knee and ankle joints were increased by changing the attachment points of Fig. 4 (see Table 1). This allowed to cope with larger forces experienced by each leg and resulted in higher rotational stiffnesses than during the synchronous hopping experiment. The knee and ankle joints controller was adapted by adding a third set point corresponding to an intermediate position in preparation for touchdown (TD) during the swing phase (Fig. 9b-top). The angle values used previously in the synchronous hopping experiment for the bent set point were used for the new TD set point and the bent set point values were changed to induce a larger flexion of the leg,



(a) Synchronous hopping motion



(b) Alternate hopping motion

Fig. 9: Top: Desired (set points) and actual position of the knee motor (at the gearhead ouput shaft). Below: Force measured by the forefoot force sensor during the hopping experiments. Flight phases (force ≤ 0) of approximately 200 ms and 160 ms can be identified for the synchronous and alternate hopping motions respectively.

in order to achieve ground clearance of the swing leg. The duration of each phase was accordingly adjusted to 360 ms, 160 ms and 200 ms for the bent, touchdown and extended set points, respectively.

In multiple experiments, the robot was able to sustain the hopping pattern for more than 15 hops. Flight phase durations of about 160 ms (see ground contact force measurements in Fig. 9b) could be achieved. However, experiments with alternate hopping motion revealed some structural weaknesses in the robot that led to mechanical failure. The most common reason for a premature end of this experiment was the breakage of one of the knee actuation wires through wear at the wire transmission pulleys. This mechanical weakness is addressed in a current redesign for the next robot version, BioBiped2.

6. Conclusions and Future Work

In this paper, the goals of the BioBiped project and the design and capabilities of BioBiped1 have been introduced. Central to the project is the transfer of previously identified biomechanical properties of the human leg towards the robot at both design and, later, at control stage. In BioBiped1, we focussed on the mechanical design and the facilitation of an elastic leg operation. The robot is specially designed to replicate typical human functionality in running and walking, with special focus on human-like segmentation and actuation of the legs by compliant mono- and biarticular structures mimicking nine main human leg muscle groups.

The different gaits – hopping, running, and walking, ordered in this atypical order by increasing the level of biomechanical complexity instead of the mechanical requirements for the hardware – will be realized on the planned prototypes. With BioBiped1, we aim for stable hopping and running abilities with the trunk constrained to vertical motion. First experimental results have been successful in demonstrating repulsive leg functionality during vertical hopping motions. The ability to passively rebound has confirmed that the robot can take advantage of the elastic elements in terms of energy recovery and has shown that the mechanical design is capable of bouncing gaits. Further, the realization of synchronous and alternate bipedal hopping gaits has demonstrated that this robot is capable of actively generating a bouncy gait with substantial flight phases. This is a very promising result on the way to running, especially as there is still room for improvement of the performance (by using hip actuation for example). The experiments also allowed us to identify a few weaknesses in the robot's hardware, such as the knee wire transmission, that will be addressed in the revision of the robot.

Next steps will include optimization of the spring selection in a simulation study and the comparison of the leg and joint function of BioBiped1 to human gait data in order to further evaluate the repulsive leg function. Also, the analyses will be extended to leg swing and cyclic locomotion with fixed trunk, approaching in this way the transition from hopping to running. Subsequently, the constraints in the hopping motion will be relaxed to generate a hopping motion which is stable in the sagittal plane. Then, by proper adjustment of the legs during swing, we aim at the transition from hopping to running.

In the BioBiped project, we aim at reaching 3D autonomous running and walking with a humanoid platform. This challenge will be adressed successively with several robot versions based on comparison between robot and human motor abilities. With this approach biomechanical insights can be directly integrated into the redesign of the robot. At the same time, this interaction may stimulate the development of novel biomechanical concepts.

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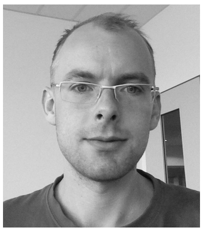

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