Three additions to passive dynamic walking; actuation, an upper body, and 3D stability

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One of the main challenges in the design of human-like walking robots (useful for service or entertainment applications as well as the study of human locomotion) is to obtain dynamic locomotion, as opposed to the static form of locomotion demonstrated by most of the current prototypes. A promising concept is the idea of passive dynamic walking; even completely unactuated and uncontrolled mechanisms can perform a stable gait when walking down a shallow slope. This concept enables the construction of dynamically walking prototypes that are simpler yet more natural in their motions than the static bipeds. This paper presents three additions to the concept of passive dynamic walking. First, hip actuation is added to increase the fore-aft stability and to provide power to the system, removing the need for a downhill floor. Second, a reciprocating hip mechanism is introduced to allow the addition of a passive upper body without compromising the simplicity, efficiency and naturalness of the concept of passive dynamic walking. Third, skateboard-like ankle joints are implemented to provide 3D stability. These ankles couple the unstable sideways lean motion to yaw (steering), a kinematic coupling which provides sideways stability when walking with sufficient forward velocity. The three additions are investigated both with elementary simulation models and with prototype experiments. All three prototypes demonstrate an uncannily natural and stable gait while requiring only two foot switches and three on/off actuators.

Keywords: Dynamic; biped; 3D.

1. Introduction

Robots that walk in a human-like manner are a fascinating topic of research. The potential benefits range from robots for entertainment or service jobs via insights in the control of complex dynamical systems to knowledge for the restoration of impaired human locomotion. Currently, one of the major challenges for research on human-like walking robots is to move from *static* walking to *dynamic* walking.

The main difficulty of human-like walking is the unilateral nature of the foot contact. The foot can only exert compressive forces to the floor and thus it can possibly tip over on one of the edges. This makes the system fundamentally under-actuated. Moreover, the unactuated degree of freedom is to be operated around an unstable equilibrium position. Therefore such systems are a challenge for classical

control techniques. The classical solution is to make sure that the tipping-over does not happen. A very crude method is *static walking* where the center of mass is kept above the floor contact polygon *and* the acceleration forces are kept insignificant. A more sophisticated method is the *Zero Moment Point* approach[38] in which the 'Zero Moment Point' (which coincides with the center of pressure[14,39]) is kept within a safe area inside the foot edges. With these methods the foot remains flat on the floor allowing the control designer to pretend that the problem of underactuation does not exist. These methods form the basis of today's most sophisticated humanoid robots[31,20].

Although the extra 'flat-foot'-constraint superficially simplifies the control problem, in reality it might result in unnecessarily complex walking systems. Therefore we will investigate systems which do not ignore the fundamental underactuation and thus show dynamic motion in the passive foot-floor contact. This has been called *dynamic walking*. An extreme example of dynamic walking is McGeer's *Passive Dynamic Walking*[23] in which not only the foot-floor contact is passive but also all other joints in the system. By showing that such systems are potentially capable of stable, human-like walking *without any control*, his work hints that human-like walking can be realized with much simpler machines than the present-day prototypes.

To move from the relatively basic state of the art in Passive Dynamic Walking (Section 2) towards more versatile and human-like machines, this paper presents three additions to the concept; hip actuation which greatly enhances the 2D stability (Section 3), a reciprocating hip mechanism which allows the addition of a passive yet stable upper body (Section 4), and a skateboard-like ankle joint which provides 3D stability (Section 5). Each of the three additions is investigated through a qualitative comparison of elementary model studies and physical prototype experiments.

2. Passive Dynamic Walking

2.1. *Historical background*

Biomechanical research has provided several hints towards the possible role of passive dynamic motions in human walking. A remarkably relevant hypothesis posed by Weber and Weber[40] as early as 1836 reads: 'Die Beine können am Rumpfe wie Pendel hin und her schwingen. (...) Unsere aufmerksamkeit wird für diese schwingende Bewegung nicht erfordert.' Mochon and McMahon[24] arrived at the same conclusion after comparing the swing leg motion with a passive double pendulum. Another hint in that direction is given by Ralston[30] who discovered that there exists an optimal walking velocity for humans; at approximately 5 km/h the specific resistance (also termed specific cost of transport, i.e. energy cost per weight per distance traveled) is minimal, a phenomenon that indicates the use of natural frequencies of the mechanical system.

Early toy makers[11] proved the applicability of the ideas by showing that the human walking motion can at least partially be generated with passive mechanisms

that move and oscillate in their natural frequencies. In 1989, McGeer[23] proposed that those passive mechanisms could serve as an alternative point of departure for the synthesis of bipedal gait. He parallelled this to the approach of the Wright Brothers, who first mastered passive gliding before they added an engine to their aeroplane. McGeer showed that a completely unactuated and therefore *uncontrolled* robot can perform a stable walk[22] when walking down a gentle slope. Since then, his work has been extended gradually by Ruina's group at Cornell University[6,12,10] up to the point where the passive approach can be regarded beyond doubt as a valid starting point for bipedal gait synthesis and robot construction.

The benefits of the passive approach are the inherent efficiency of the walking motion, the natural-looking motions, and the simplicity of the required construction. The development towards a more human-like versatility should be taken step-by-step (figuratively), which can be seen as both a benefit and a drawback of this approach. The drawback is that, although the motions of the early machines are uncannily natural, the general public is quickly disappointed with the incompleteness of the system (e.g. no upper body, lateral constraints to ensure only two-dimensional dynamics, no velocity control). This makes the passive approach unattractive for industrial developers. The required incremental addition of versatility does, however, provide ample opportunities to discover fundamental dynamic properties. As such, the passive approach is the most appropriate point of departure for academic research into gait synthesis.

2.2. *State of the art*

Since McGeer, much research has been done on passive dynamic walking, but even more remains to be done. McGeer left the field after the completion of a biped with knees which was laterally constrained (2D dynamics) by a symmetric construction with two pairs of legs. Simulation studies on fully passive models were performed by Garcia[13] and Goswami[15], whereas Hurmuzlu[17], Spong[33], Van der Linde[37] and Asano[3] added some form of actuation and control. Wisse[42], Piiroinen[27], Adolfsson[1,2], and Kuo[19] simulated near-3D models, whereas Coleman[8] simulated a fully passive, full 3D model. That last model was one of the few that was matched to a physical prototype[9]. Other prototypes were built by Collins[10], Van der Linde[36], Ono[25,26] and Tedrake[34], whereas Pratt[28] included passive dynamics in an otherwise active robot.

Almost all walkers in this list consist of legs only, most of them are fully passive, and many exist only as computer models. Also, all of them require a disturbance-free environment. To advance from this state of the art towards human-like walking capabilities, at least the following topics need to be addressed:

- the robustness in 2D must be increased,
- an upper body must be added,
- robustness in 3D must be obtained,
- the walking velocity must be controllable,

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- the walker must be able to start and stop,
- the walker must be able to turn,
- the walker must be able to stand up after a fall,
- etc.

The increase in complexity and actuation must be carried out step-by-step. For each addition, it should be ensured that the beneficial characteristics of passive walking (efficiency, naturalness, and simplicity) are preserved, and that the fundamental dynamic properties and effects in the entire system with the new addition are understood. The current paper focuses on the first three topics; an increased robustness in 2D, the addition of an upper body, and the search for robustness in 3D.

2.3. *Stability analysis*

Dynamic walking requires a special form of stability analysis; not the classical approach with linearized, continuous control, but rather the numerical tools from nonlinear dynamic systems theory. The walking system (e.g. Garcia's 'Simplest Walking Model'[13], Fig. 1) is regarded as a dynamic system in a limit cycle; a repetitive motion for all but one of its coordinates (forward progression is non-cyclic). To analyze the stability of such systems the standard method of Poincaré Mapping is applied (originally introduced by Poincaré for the analysis of celestial mechanics and the discovery of chaos). For a well-defined state of the system (the Poincaré Section), usually the state at heel contact, it is analyzed how the cyclic coordinates and velocities progress from step to step. In the limit cycle, the system state is equal at every pass through the Poincaré Section, termed a *fixed point* on the *Poincaré Map*. If errors upon the fixed point decay step after step, the walking motion is asymptotically stable. If on top of that the *basin of attraction* is sufficiently large, the system possesses a practical stability. The basin of attraction (Figs 2 and 3) is the range of errors for which the system still converges to the limit cycle. If it is sufficiently large, the system under consideration is a candidate for the synthesis of human-like walking machines. These analyses must be performed for each addition to the passive walkers to investigate its practical viability.

3. Hip actuation for power input and stability

3.1. *Elementary model study*

The first addition to the concept of passive dynamic walking is actuation in the hip joint which greatly enhances the 2D (forward) stability. Although the purely passively walking prototypes demonstrate convincing walking patterns, they all require a smooth and well adjusted walking surface. A small disturbance (e.g. from small errors introduced with a manual launch) can still be handled, but larger disturbances quickly lead to a failure[32], see Fig. 3. The most distinct failure is a fall forwards; the swing leg is not timely in a forward position to catch the robot for
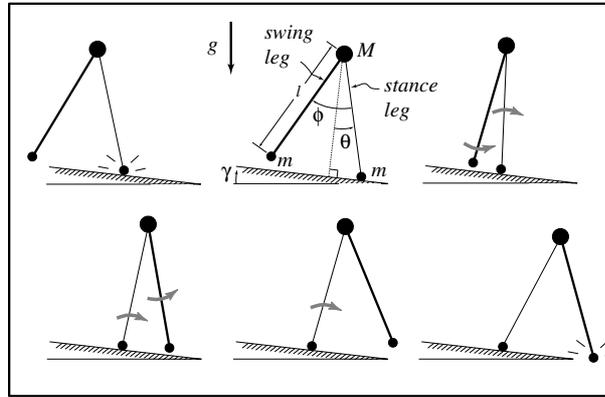
Fig. 1. A typical passive walking step. The new stance leg (lighter line) has just made contact with the ramp in the upper left picture. The swing leg (heavier line) swings until the next heelstrike (bottom right picture). The top-center picture gives a description of the variables and parameters that we use. θ is the angle of the stance leg with respect to the slope normal. ϕ is the angle between the stance leg and the swing leg. M is the hip mass, and m is the foot mass. l is the leg length. γ is the ramp slope, and g is the acceleration due to gravity. Reprinted with permission from Garcia *et al.* [13].
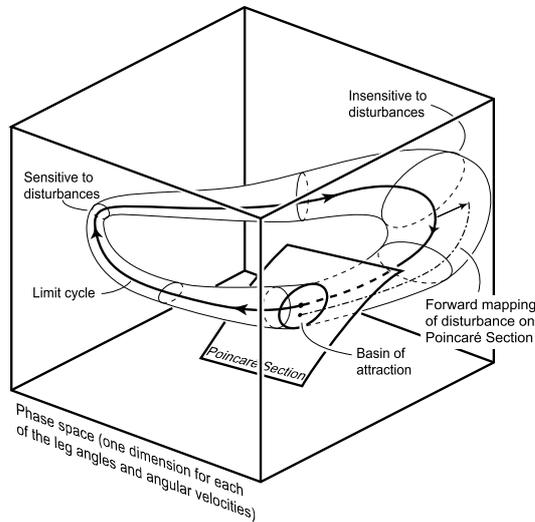

Fig. 2. Stylized phase graph of walking motion.

its next step. A second type of failure is an instability that manifests itself as a diverging alternation of short and long steps. This is the result of the interaction between step length, energy input, and energy loss at the heel strike impact.

Both types of failures can be prevented by means of a simple control rule which accelerates the swing leg to a preset forward position[45]; the faster the swing leg
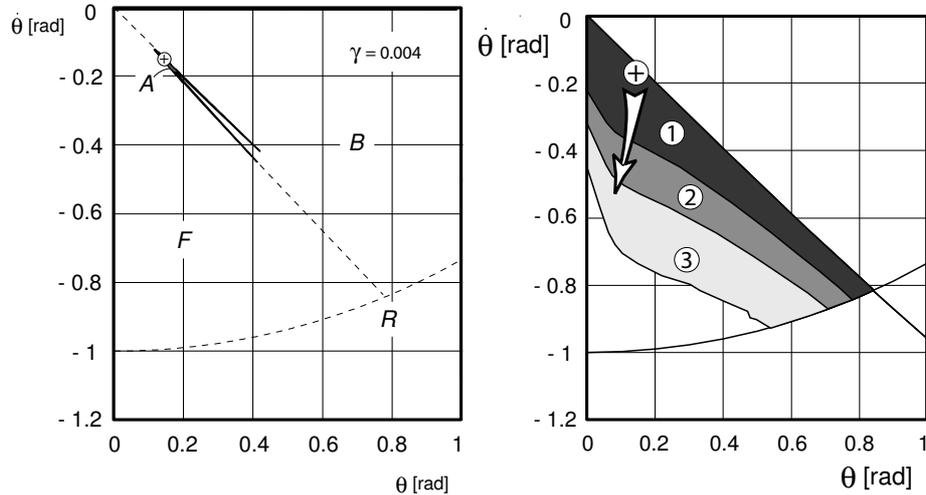
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Fig. 3. **Left:** Poincaré section for the simplest walker (Fig. 1 with initial stance leg angle θ and velocity $\dot{\theta}$ together with failure modes; falling Forwards, falling Backwards and Running, and the basin of Attraction of the cyclic walking motion $(\theta, \dot{\theta}) = (0.1534, -0.1561)$ [rad] (indicated with '+') at a slope of $\gamma = 0.004$ [rad]. Reprinted from [32]. **Right:** Basin of attraction of the simplest walker with active hip spring. The setpoint of the hip spring is $\phi_{sp} = 0.3$ and critical damping is applied. The higher the hip spring stiffness, the larger the basin of attraction; $k = 25$ leads to area (1), $k = 50$ leads to area (2), and $k = 100$ leads to area (3). The fixed point is for all three stiffness settings approximately the same, located at the '+'. A disturbance from a step down in the floor would result in initial conditions away from the fixed point in the approximate direction of the white arrow. Reprinted from [45].

is swung forward, the more robust the walker is against disturbances. The exact motion of the swing leg is irrelevant which allows for a wide variety of possible implementations. In the most extreme (and theoretical) case, the swing leg is instantaneously brought to its forward position, making the dynamic behavior comparable to that of a *rimless wheel*[7], i.e. a cart wheel without the rim, walking on its spokes.

For practical robots, instantaneous positioning is impossible because the legs have a non-zero inertia. We investigated the stability improvement as a function of different levels of actuation. The hip actuation is implemented in the model with a critically damped spring with a forward setpoint, where a higher spring stiffness means a higher level of actuation. Fig. 3 shows that the basin of attraction increases as a function of the level of actuation, leading to the conclusion that the faster the swing leg is brought forward, the better the model is resistant against disturbances. Another important effect of the leg inertia in real prototypes is the fact that the hip actuation also provides an energy input into the system. This side-effect eliminates the need for downhill walking and thus drastically increases the usability of the concept of passive dynamic walking.
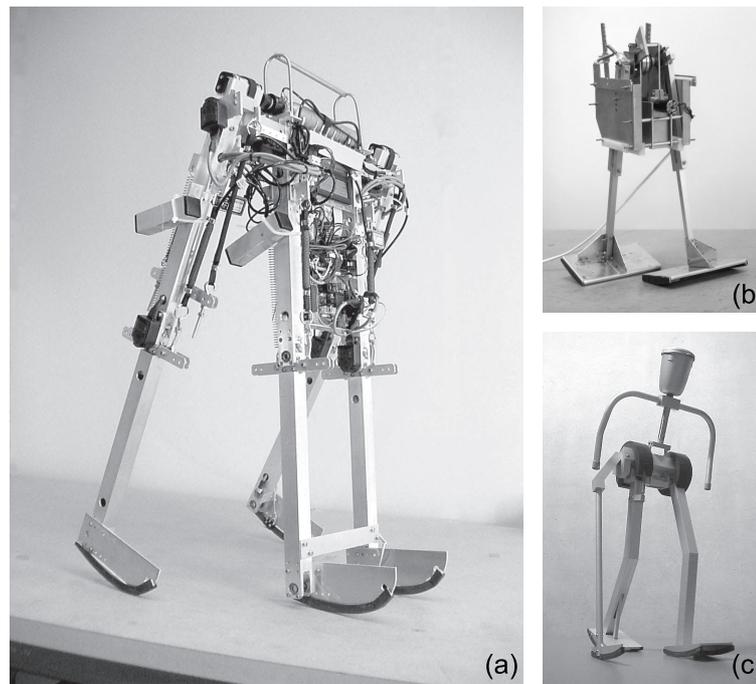
3.2. *Prototype experiments*

Fig. 4. 2D machines built during the project: (a) Mike, (b) Latch Walker, (c) Museon Walker.

We applied the proposed swing leg control to our prototype 'Mike' (Fig. 4a). Mike weighs 7 kg and measures h x b = 0.7 x 0.4 m. An elaborate description of Mike can be found in[46] while movie clips of Mike in action are available at our web site[21]. Mike has four legs symmetrically paired, giving it approximate 2D behavior. It differs from the simplest walking model by having knees, a distributed leg mass, round feet and by walking on a level floor (no slope!).

Mike is actuated with a total of eight McKibben muscles; lightweight pneumatic actuators that act like springs with a stiffness proportional to the internal pressure[5,35]. The McKibben muscles are arranged according to Fig. 5. The hip joint is actuated with an antagonistic pair of muscles (A) and (B) providing a combined joint stiffness. The knees are actively extended with McKibben muscles (C) and (D) which are counteracted by weak passive springs. There is no ankle actuation; the arc feet are rigidly attached to the shanks.

The McKibben muscles are fueled from a 5.8 [MPa] CO_2 container via a two-stage pressure regulator and via electromagnetic valves that are activated by switches underneath the feet. The second-stage pressure regulator output is manually adjustable between 0.1 and 0.6 [MPa] resulting in a hip joint stiffness up to
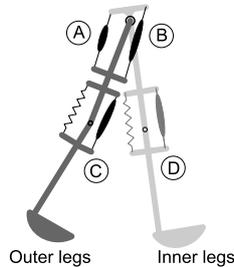
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Fig. 5. Schematic structure and muscle attachments of Mike.

5 [Nm/rad] and a damping somewhat less than critical damping (estimated by observation). It is not feasible to perform a proper mapping between this stiffness in Mike and the scaled stiffness in the simplest walking model due to the extensive differences between the two, such as leg mass, foot arc radius, muscle non-linearities and significant air flow dynamics. Therefore the comparison between the two will be of qualitative nature only.

If a valve is switched 'on', the muscle is filled from the pressure regulator output; if switched 'off' it reliefs into atmosphere. For example, at activation of the inner leg foot switch, the outer knee muscles (muscle C in Fig. 5) are switched 'off' to allow this knee to bend. A manually tuned 400 [ms] later they are switched back 'on', ensuring a properly extended knee for the next step.

The proposed swing leg control is implemented by alternating the states of the antagonistic hip muscles. When the foot switch of the inner legs is activated, muscle B in Fig. 5 is switched 'on' and muscle A is switched 'off'. At the next step this is inverted. As a result, the hip joint has a constant stiffness but a setpoint that alternates between ϕ_{sp} and $-\phi_{sp}$. The joint stiffness can be adjusted without altering the setpoint. We want to emphasize that there is no feedback control other than this once-per-step switching between preset muscle pressures. We dub this 'feet-forward control'.

Mike walks at 0.4 m/s (0.6 s per step), see[21] for video evidence. We would have liked to create a figure of its basin of attraction like Fig. 3. However, the combined limitations on the number of experiments to be performed and on the physical possibilities to create controlled disturbances have led us to concentrate on one representative disturbance, namely a step-down.

In the experiments the prototype walks steadily and then takes a step down of increasing height, see Fig. 6. Such a step down results in a larger stance leg velocity at the subsequent step as sketched with the white arrow in Fig. 3. The larger the step down height, the larger the arrow. If a larger hip muscle stiffness indeed allows a bigger step down, then our swing leg control rule is validated.

The stability results are shown in Fig. 7. A hip muscle pressure lower than 0.35 [MPa] did not provide stable walking at all, not even without disturbances.
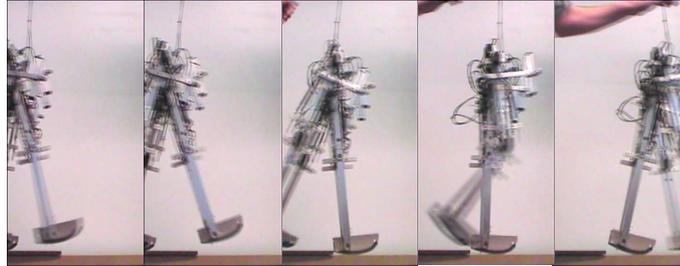
Fig. 6. Experiment with Mike walking on level floor and taking a step down as a representative disturbance.

When the pressure was increased, a larger step down could be handled. The muscles prohibit pressures higher than 0.55 [MPa]. Fig. 7 clearly shows a better robustness against falling forward with a higher hip pressure which corresponds to a faster swing leg motion.
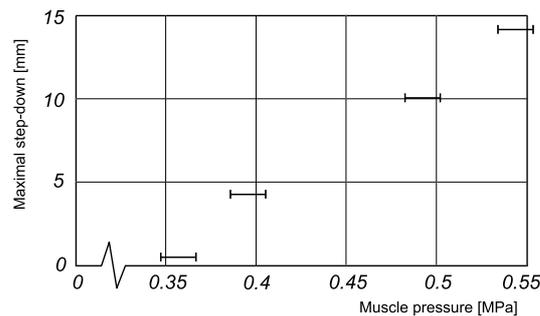

Fig. 7. A higher hip muscle pressure setting (corresponding to a higher hip joint stiffness) results in a larger step-down size and thus in a better resistance against disturbances.

After these successful results, the same form of stabilization by means of an accelerated swing leg was used to construct two demonstration prototypes. The 'Latch Walker' (Fig. 4b) walks on level floor using a single, uncontrolled DC motor (its constant energy input is regulated by means of a wind-up spring and a latch in the hip joint). The 'Museon Walker' (Fig. 4c), which was on display in a hands-on technical exhibit, requires a sloped walking surface and obtains its swing leg acceleration from a mechanism at the hip joint which effectively lowers the center of mass to provide energy to the swing leg.

3.3. *Conclusion*

Both the elementary simulation and the prototype experiments demonstrate that a simple controller can solve the problem of falling forward; all it needs to do is to

get the swing leg timely in a forward position. Both the elementary simulation and the prototype experiments show a similar qualitative effect; the higher the level of actuation, the better the robustness against disturbances. For implementation of this form of control, a damped hip spring with a forward setpoint already suffices. The specific control and actuation details are not important as the same result can be achieved with any configuration if it is based on the following rule: *"You will never fall forward if you put your swing leg fast enough in front of your stance leg. In order to prevent falling backward the next step, the swing leg shouldn't be too far in front."* A controller designed according to this rule is easy to implement, because no a-priori knowledge of the passive dynamic walking motion is needed.

4. Reciprocating hip mechanism for passive yet stable upper body

4.1. *Elementary model study*

The second addition to the concept of passive dynamic walking is a reciprocating hip mechanism for the addition of a passive upper body. The reciprocating hip mechanism was first explored in a highly simplified model consisting of four point masses connected by rigid, massless links[44] (Fig. 8). The study revealed the possibility of fully passive walking with an upper body by means of a reciprocating hip mechanism. For a lightweight upper body, the dynamic effects of the passively swinging legs are dominant. When the weight of the upper body increases, a hip spring is required to maintain the upright position as the equilibrium position. The study showed that a suitable spring stiffness can be found for any mass distribution.
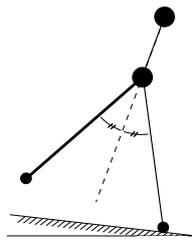

Fig. 8. Simple model for preliminary study of passive reciprocating hip mechanism.

A parameter study with the simple model showed the effects of the upper body on the stability and the energy efficiency of the walking motion. One clear result is that the fore-aft mass distribution has a strong influence on the existence and the stability of the cyclic walking motion, matching McGeer's finding of a similar influence of the fore-aft mass distribution in the legs of his walkers. Conversely, the walking motion is very tolerant to changes in the vertical mass distribution. A weak but counterintuitive effect was found, as a higher center of mass provides a better robustness against disturbances. Moreover, elevation of the center of mass also

improves the energy efficiency. Altogether, the preliminary study was strongly encouraging to the construction of prototypes with an upper body connected through the proposed reciprocating hip mechanism.
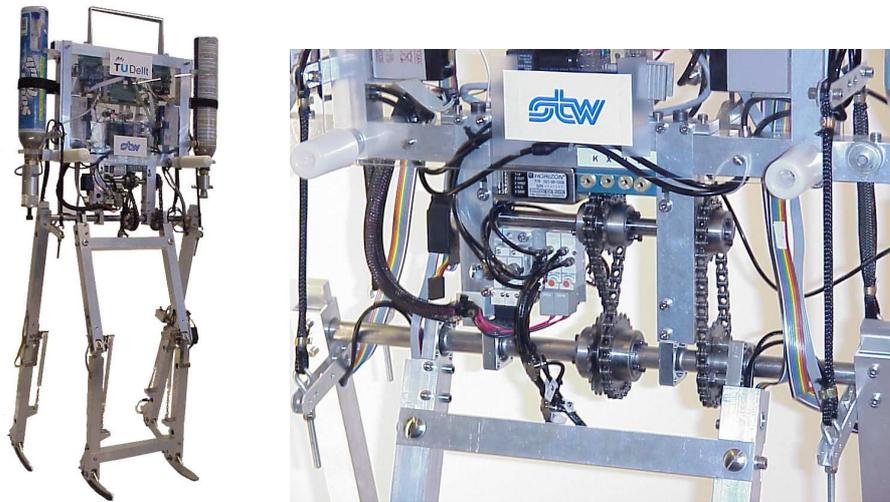
4.2. *Prototype experiments*

Fig. 9. **Left:** Prototype Max; a 2D passive dynamic walking robot with an upper body connected to a reciprocating mechanism at the hip. **Right:** The reciprocating hip mechanism in the prototype. The outer legs are rigidly attached to the hip axle, the inner legs can rotate freely. The hip axle is connected through bike chains via an auxiliary axle to the inner legs.

The idea is validated in the prototype 'Max'[41] (Fig. 9), which weighs 10 kg, measures h x b = 1.1 x 0.5 m and walks at 0.4 m/s (0.8 s per step). Max is the direct successor of Mike (Fig. 4a); the design and the applied components are more or less identical except for the addition of an upper body and some minor improvements. The improvements include 1) switchable knee latches which remove the need for knee muscles, 2) ankle joints which are frozen now but allow ankle actuation in the near future[16], and 3) a much larger on-board CO_2 storage (two canisters of 450 grams, each of which enables 30 minutes of continuous walking).

The reciprocating hip mechanism is implemented with an auxiliary axle connected to the legs with one straight and one cross-over chain (Fig. 9). In hindsight, it is valuable to report that this solution requires extra attention to the problem of slack in the chains. Also, one must be aware that rather large torques are transmitted through the chainwheels and axles, especially when the prototype occasionally falls. Nonetheless, for our relatively lightweight prototype this solution is satisfactory. Other possible mechanisms include a four-bar linkage, a differential

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gearbox, or cables and pulleys (as applied in some gait orthoses[18]). Alternatively, the reciprocating hip action can also be obtained in fully actuated robots where a sub-controller maintains the upper body in the dissection angle[29,4]. We would like to emphasize that any of these solutions, mechanical or controlled, are simple in that they only require *local* information, i.e. the absolute angle of the body or legs are irrelevant, only the relative angles between the three.

Fig. 10. Video stills illustrating the walking motion after a manual launch.

Fig. 10 illustrates the walking motion after a manual launch. On a reasonably flat and level floor (height variations of less than 3 mm per step), the prototype could easily perform sustained walking with series of over 50 consecutive steps. While tuning the prototype for optimal performance, we found the same parameter influences as predicted by the elementary simulation model. The prototype is tolerant to variations in most of the parameters (e.g. 1 kg of extra mass on the upper body has no noticeable effect), except for those parameters that affect the forward velocity. The forward velocity is the net result of the velocity increase during the stance phase and the instantaneous velocity decrease at heel strike. The velocity increase is determined by the amount of time that the robot's center of mass spends *behind* the foot contact point (deceleration) and the amount of time spent *in front of* the contact point (acceleration). Any parameter that influences these has a strong effect on the walking motion; with too much deceleration the walker will have a tendency to fall backwards whereas with too much acceleration the resultant walking velocity will be high and thus the chances of falling forward increase. For our 10 kg walker, a 500 g additional mass that can be attached up to 100 mm in front or behind the hip joint already provides sufficient tuning possibilities. In our opinion, the automatic control of the fore-aft balance will be one of the major improvements for future dynamic walking robots.

4.3. *Conclusion*

In conclusion, the reciprocating hip joint allows a straightforward addition of a passive upper body to the concept of passive dynamic walking. Both the elementary simulation model and the prototype show that the parameters of the upper body barely influence the walking behavior and the stability. There is almost no effect of an increase of the mass or a vertical displacement of the center of mass. Only the fore-aft position of the center of mass is important, as it regulates the average forward walking velocity, and thus the chances of falling forward or backward.

5. Skateboard-like ankle joint for 3D stability

5.1. *Elementary model study*

The problem of lean instability (the walker is an inverted pendulum in the frontal plane) is usually approached in an isolated fashion; researchers find solutions for the inverted pendulum problem *per se* such as sideways foot placement or reaction torques from the upper body[19]. However, when the full 3D system is regarded, another solution presents itself. Similar to skateboards and bicycles, one could use *steering* (yaw) to stabilize *lean*, at least as long as the system is moving forward with sufficient velocity. The same principle is applicable for walking, and can be implemented in walking robots with an ankle joint that kinematically couples lean to yaw.
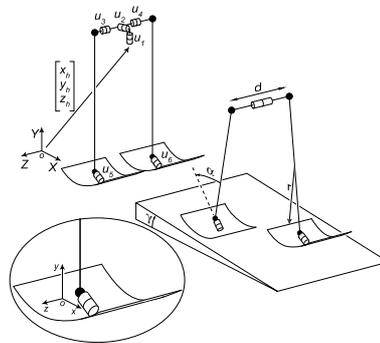

Fig. 11. Simplified point-mass model used to analyze the stabilizing effect of a tilted ankle axis that couples lean to yaw.

We investigated the concept with a simulation study[43]. The simplest model for this purpose is a 3D cousin of Garcia's two-dimensional 'Simplest Walking Model'[13] which consisted of one finite point mass at the hip joint, two infinitesimally small point masses at the feet, and massless rigid links in between, interconnected with a frictionless hinge at the hip. Our model (Fig. 11) is a 3D extension of this; the hip has gained a finite width and the hip mass is divided into two point masses at the

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extremes of the massless hip axle. The degrees of freedom are the coordinates and the yaw and lean angles of the center of the hip axle, the two leg pitch angles, and the two ankle angles. The ankle axes are mounted in the x-y plane at an angle α with respect to the vertical. Note that the ankle axes have no component in the z-direction, unlike conventional robot designs or the human ankle. The 'normal' ankle functionality, rotation around the z-axis, is realized by means of the roll-off motion of the feet. The feet are (partial) cylinder shells with the cylinder axis perpendicular to the ankle axis. The foot-floor contact is modeled as a perfectly rigid cylinder-plane contact with only one degree of freedom; roll in a direction perpendicular to the cylinder axis. The width of the feet is not specified and is assumed to be sufficient to prevent sideways tipping over the edge.

The simulation results can be summarized in four conclusions. First and foremost, the ankle joint indeed provides stability for the 3D walking model. Moreover, the simulation study[43] shows that it is highly robust against disturbances (allowing a 100% deviation on most of the initial conditions) and against parameter changes (allowing a sideways center of mass offset of 5% of the leg length). Second, the simulation study shows that these stability results can only be achieved if the ankle joint is applied in combination with the hip actuation as described in Section 2. Without that, the (fully passive) model is barely stable. Third, the model is stable only if the forward walking velocity is above a certain critical value, a behavior which is similar to that of a skateboard or a bicycle. The critical velocity is a function of the orientation of the ankle joint. The more vertical the joint is oriented, the lower is the critical velocity. Fourth, the ankle joint provides an effective means for direction control; a slight asymmetry in any of the parameters (such as a sideways mass offset) results in a walk on a curved path. All together, the simulations with the elementary model predict a sufficient robustness against disturbances to warrant the construction of a physical 3D prototype.

5.2. *Prototype experiments*

The ankle joint is tested in the prototype 'Denise' (Fig. 12), which weighs 8 kg, measures h x b = 1.5 x 0.3 m and walks at 0.4 m/s (0.8 s per step). Denise is a direct successor of Max (Fig. 9) and has the same hip actuation, reciprocating hip mechanism and controllable knee latches. The prototype has five internal degrees of freedom (Fig. 12); two ankles, two knees, and one at the hip (the arms are mechanically connected to the opposing leg). The ankle joints are mounted in the non-human orientation as proposed above, namely pointing forward and downward without a component in the lateral direction (Fig. 13, making an angle $\alpha = 25°$ with the leg. The ankles are provided with a high torsional stiffness (Fig. 13).

The contact between the foot and the floor is meant to constitute one degree of freedom, namely forward rolling on the foot's cylindric shape. The foot dimensions are given in Fig. 13. The foot has two equal contact rails on the sides to provide as much yaw torque resistance as possible for a given foot width. The degree of
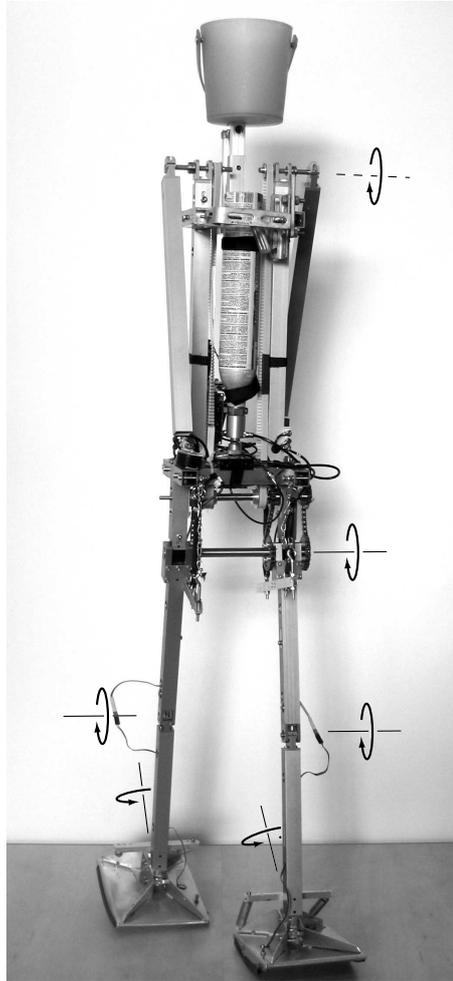
Fig. 12. Denise, minimalistic 3D dynamic walking robot with 5 degrees of freedom; two ankles, two knees, one at the hip, and the arms are rigidly coupled to the hip angle.

freedom in the ankle allows for ground contact with both rails in all situations, but due to the ankle spring it is still possible that the foot tips over sideways on one of the rails (suddenly adding two more degrees of freedom, namely lean and yaw of the foot). Because the stabilizing effect of the ankle joint only exists with full foot contact, we tuned the ankle spring so that this undesired loss of contact does not occur normally.

The main result to report is that Denise walks stably. An illustration of the walking motion is given in Fig. 14. With a velocity of 0.4 m/s (0.8 s and 0.3 m per step), it is slower than a human being. It uses 0.3 gram CO_2 per step which allows it to walk for 20 minutes on a single canister. From observations during
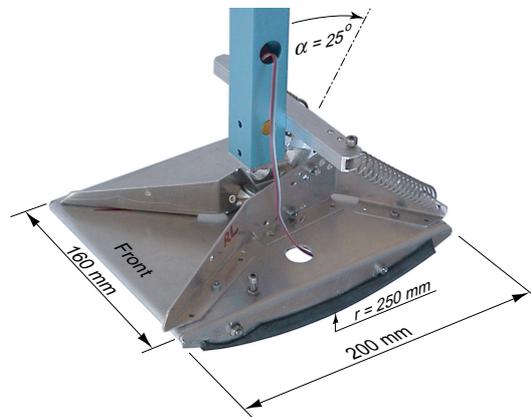
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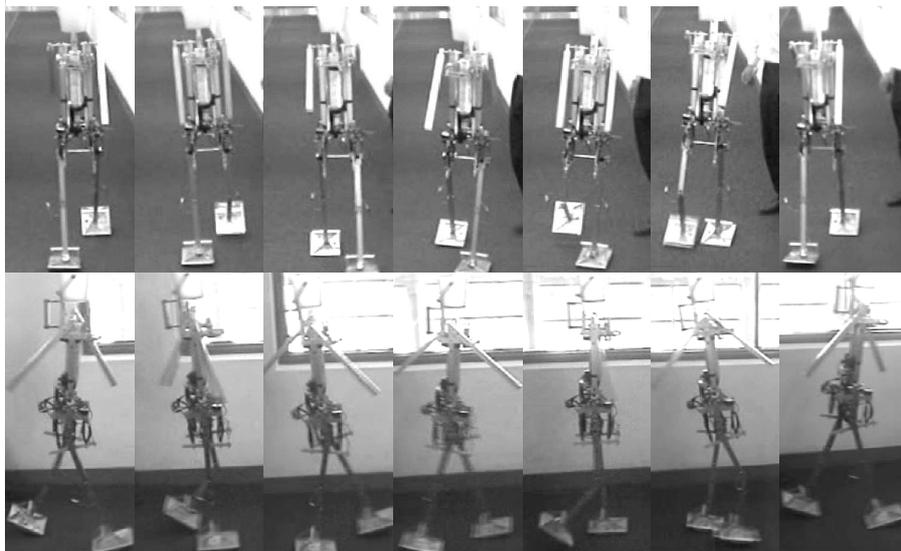Fig. 13. Details of the (right) foot.

Fig. 14. Video stills of Denise walking, two steps (one stride). The video shows a slight turn to the right as a result of a disturbance in the floor.

the experiments we conclude that the prototype is not optimal yet. The prototype demonstrates more frequent failures than the prototypes Mike and Max (Figs 4a and 9). First, the ankles of Denise had to be equipped with torsional springs and with purposeful friction in the joint before stable walking was achieved. These two features were not part of the elementary simulation model and should not be necessary. We hope to study the influence of the spring and friction in the near future.

Second, the foot contact is not entirely yaw-free; at the instant of knee strike of the swing leg, the asymmetric impulse cannot be resisted by the friction torque of the stance foot. The prototype is observed to change heading at some of the knee strikes, which is a source of disturbances. Therefore, one of the first directions for future research is to decrease the mass of the foot to decrease the adverse impulse at knee strike. Third, the prototype falls approximately one out of twenty steps due to irregularities in the floor, and when this occurs it is always a fall forwards. The solution to this problem has already been presented in Section 3 of this article; apply more power to the hip actuators to bring the swing leg forward more quickly. Unfortunately, we have currently reached the upper power limit of our pneumatic system. A redesign is required before we can increase the level of hip actuation and thereby the stability of the prototype. This current limitation is the reason that we can only crudely recognize the effects that were predicted with the elementary simulation model; the prototype does *not* walk stably 1) when using less than maximal pneumatic power (with the current system) to bring forward the swing leg, 2) when using a less vertical ankle joint (we tried ankle joints of 45º and 25º with respect to vertical, it failed with the first and succeeded with the latter), 3) when walking slower than maximally possible (which we tune with the fore-aft mass distribution). A more powerful actuation system is required before we can obtain more quantitative results.

5.3. *Conclusion*

Both the elementary simulation model and the prototype demonstrate 3D stability. The skateboard-like ankle joint forms a simple mechanical ingredient for the design of stable dynamic walking bipeds. The stabilizing effect is only present when walking with a substantial forward velocity and requires the presence of hip actuation as proposed in Section 3 of this article.

Although the idea is strongly linked to a mechanical implementation in the form of a tilted ankle axis, there are many alternative ways of implementation, either mechanically or via control, in the foot, ankle, leg, or hip. The central idea is that, if there exists a forward velocity, a sideways fall can be averted by steering in that direction.

6. General conclusions

In this article we propose three additions to the concept of passive dynamic walking:

- Actuation at the hip joint results in a drastic increase of the 2D stability of the walkers; the faster the swing leg is brought to a predefined forward position, the smaller the chance that the walker falls forwards (the most frequent failure). Additionally, this form of actuation provides sufficient energy to the system to remove the need for a downhill walking surface.
- A reciprocating hip mechanism allows the addition of a passive upper body

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> without compromising the efficiency, stability, or simplicity of the concept of passive dynamic walking,
>
> - Skateboard-like ankle joints (which point forward and downward without a lateral component) provide stability for 3D bipeds. The ankle joints are only effective when in combination with the proposed hip actuation and when walking with sufficient forward velocity.

The three additions have enabled us to construct a prototype with a human appearance (two legs with knees, upper body, arms) and a stunningly natural gait. The most significant achievement is that these results were obtained while using a minimal control system; the entire control system consists of two foot switches which trigger three on/off actuators (one hip actuator and two knee latches). Dynamic walking can be obtained with elegantly simple machines.

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