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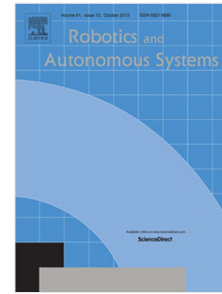
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Towards a 3D passive dynamic walker to study ankle and toe functions during walking motion

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ABSTRACT

The ankle-foot complex in the human body is one of the major determinants in normal human walking. Most of the research study ankle and foot motion by observing people as they move, measuring desired kinematic and kinetic data indoor or outdoor, and numerical simulations in computer. However, very few studies are able to explore the fundamental mechanical principles underlying human musculoskeletal system. In this paper, we developed a three-dimension (3D) passive dynamic walker with flat feet, toes and ankle springs to investigate the impact of the ankle and toe stiffness in the walking motion. The results suggest that the ankle springs have a main impact on the walking motion, where the anterior spring, over any other position, plays a main role in providing sagittal stability. The springs from the sagittal plane control the pitch angle of the robot which impacts on its velocity and step length. The stability got worse along with the step length and velocity increasing especially when the step length overcame 8 cm. The fact that the best configuration of the ankle joint has stiffer stiffness in the sagittal plane than the coronal plane complies in nature with humans where Tibialis Anterior, Soleus and Gastrocnemius muscles are much stronger than other muscles around the ankle. Furthermore, it can be stated that the medial toe plays a more important role than the lateral one, as blocking the medial toe with the stiffest joint (rigid joint) has a negative effect on walking motion. In conclusion, we show that the ankle stiffness of the robot in anterior-posterior position should be higher than that in medial-lateral position and the stiffness in any position should exceed a minimum level to maintain walking stability. Also, adding toes (medial one should be softer than the lateral) in the foot of the robot may benefit biped locomotion especially when taking longer step length.

Keywords: biologically inspired robot, passive walker, biomechanics, ankle, toe

1. Introduction

Human walking is a dynamic, partly self-stabilizing process relying on the interaction of the biomechanical design, i.e., the musculoskeletal system, with its surroundings. Nature has created successful solutions adapted to different uses and environments that develop great capabilities with apparent simplicity. The most conventional methods of studying human walking are observing people as they move [1-3], measuring desired data by electrical devices during experiments on a real person (e.g., motion capture [4-6], surface electromyography [7-11], medical imaging [12-14]), and numerical simulation [15-19] in computer (e.g., rigid body modelling and continuum mechanics modelling), etc. However, very few studies are able to explore the fundamental mechanical principles underlying human musculoskeletal system as the results could not be validated in a real person.

Indeed, biologically inspired bipedal robots can provide an attractive alternative approach to investigate the what-if questions in human movement by examining the important components in a scientific cycle of producing hypotheses, conceptions and assumptions, testing them in experiments and adjusting them properly towards new theories. Repeatable, parameterized experiments can be conducted in the robot model by programming. Relevant variables and parameters immeasurable in human trials can be monitored by implementing multiple sensors (e.g., internal forces) in them. The morphology of robots can be changed in a systematic way to perform different tasks. They can perform movements that could be dangerous or even unreasonable for human, exploring the optimization of human movements (e.g., motions, exercises or sports that are helpful for human health). The past decades, especially after ZMP criterion [20, 21] and its relation to human walking stability being proposed in 1969, have seen great progress and advance in bio-inspired bipedal robots that aim at complexities such as ASIMO [22], NAO [23, 24], Petman [25], Atlas [26], etc. Yet, most of those robots are incomparable with humans from a biomechanical point of view. Recently, passive dynamic walkers (e.g., McGeer biped [27], MIT biped [28], Denise [29] and Cornell biped [30]) which base their locomotion on natural dynamics solely are proposed as the new design and control paradigm to investigate human biology, especially biomechanics and neuroscience.

Human ankle-foot complex plays a determinant role in human locomotion as it is the only part which contacts with the environment. Understanding the natural regulation of ankle-foot functions during walking motion is necessary to explore how humans interact with environments, and also provide a foundation design principle for the development of humanoid robots. In literature, ankle function has been studied extensively in various conditions. System identification analyses [31-34] are widely used to quantify ankle joint parameters during postural conditions, in which joint dynamics are obtained through the analysis of the relation between the input (position, torque and EMGs signal) and output (torque and position) records. Wearable ankle robots [35] or specific instrumented platforms [36] (e.g., 3D motion capture system [37]) have recently been developed to estimate joint functions during walking. However, those studies have not characterized the ankle-foot complex functions throughout the complete gait cycle, and our knowledge of ankle and foot regulations during dynamic tasks such as walking is still incomplete.

Recently, some conventional biped robots equipped with new design of ankle or toe joints has come out to study the function of human foot in gait or human-like biped locomotion (particularly walking or running). Otani et al [38-40] developed a biped robot with leaf springs (acted like torsion spring in the sagittal plane) in the ankle to explore human running. It can perform active push-off during running driven by active knee, hip and passive ankle. In 2006, WABIAN-2R robot [41] was built by Waseda University to achieve human-like walking. A passive toe that can rotate freely in the sagittal plane is added in the foot, but the main contribute to the ability of mimicking the knee stretched, heel-contact and toe-off motions of human walking are the powered ankle, knee and hip joints. There is no further study on the function of the toe. WABIAN-2R evolved in 2010, where a new foot mechanism containing medial longitudinal arch and two toes [42] has been applied to figure out the function of the arch structure in human foot. The motion of the medial toe is limited by connecting a stainless wire to the arch and the lateral toe can perform free rotation in the sagittal plane. Hashimoto et al [42] found that the changes of the elasticity of the medial longitudinal arch could reduce foot-landing force during walking, but the toes function has still not been answered. Moreover, HRP-2LT [43] and HRP-4C [44, 45] used passive or active toes to imitate human walking pattern. From the standpoint of engineering, these robots with special design in the ankle or toes can imitate human-like locomotion gait (e.g., toe-off) using high-

torque motors mounted in the joints and sophisticated control algorithm. However, they have neither quantitatively evaluated how the mechanical impedance of ankle or toes affects biped walking or running from a biomechanical point of view, nor considered the medial-lateral (i.e., in the coronal plane) elasticity or compliance of the ankle.



Figure 1. 3D Bipedal robot with flat foot, toes and ankle springs.

In this paper, we developed a 3D passive dynamic walker (Figure 1) to be used as a platform to evaluate the ankle and the toe functions, especially the stiffness, during walking motion. The research focused on the foot, ankle and toes design, trying to mimic human walking and understand the advantages of human ankle-toes structure. Previous works in the literature developed bipedal robots with flat feet and ankle springs (e.g., the walker from Keio University [46, 47]) lack of further research on the effect of each spring position in the walking motion. They were limited to set the same type of spring in all the ankle positions, instead of combining different stiffness springs at the same time and analyzing their impact on the motion and stability of the robot. Section 2 describes the basic biomechanics of the ankle-foot-toe complex in human body during normal walking. Section 3 presents the design concept of the passive dynamic walker. Section 4 outlines a series of walking tests to investigate the effects of each ankle spring position (anterior, posterior, lateral and medial) in the walking motion, to analyze the impact of the ankle springs within the sagittal and coronal planes to the roll, pitch and the forward swinging motions of the leg, to study the toes effect on the stability in function of their joint stiffness at medial and lateral position. Section 5, we discuss the results and the limitations, conclude this paper, and suggest new guidelines and designs to be followed in the future research.

2. Biomechanics

The primary task of the ankle-foot complex is to provide an adaptable, stable, and efficient interface between the body and the ground during human locomotion. This task requires the ankle and the foot to be sufficiently pliable during early stance phase to conform to various surface terrain, to absorb and translate energy while maintaining whole-body stability, and to rapidly achieve sufficient rigidity during late stance phase to propel the body forward using the rigid lever of the longitudinal arch [48].

The key movement of the ankle joint complex are dorsiflexion and plantarflexion, occurring in the sagittal plane, and inversion/eversion occurring in the coronal (frontal) plane (see Figure 2). Due to the projection of the foot anteriorly from the coronal plane of the body, the terminology describing motion of

the foot differs in several important ways from standard descriptions of motion in other areas of the body [48]. First, the inversion and eversion represent motion in the coronal plane about an anterior/posterior axis (known as abduction/adduction elsewhere in the body), which occur primarily at the subtalar joint and can be demonstrated by moving the plantar surface of the foot to face medially (inversion) or laterally (eversion). Second, flexion/extension of the foot is termed dorsiflexion and plantarflexion respectively. This motion occurs around a medial/lateral axis in the sagittal plane, i.e., primarily at the talocrural joint.

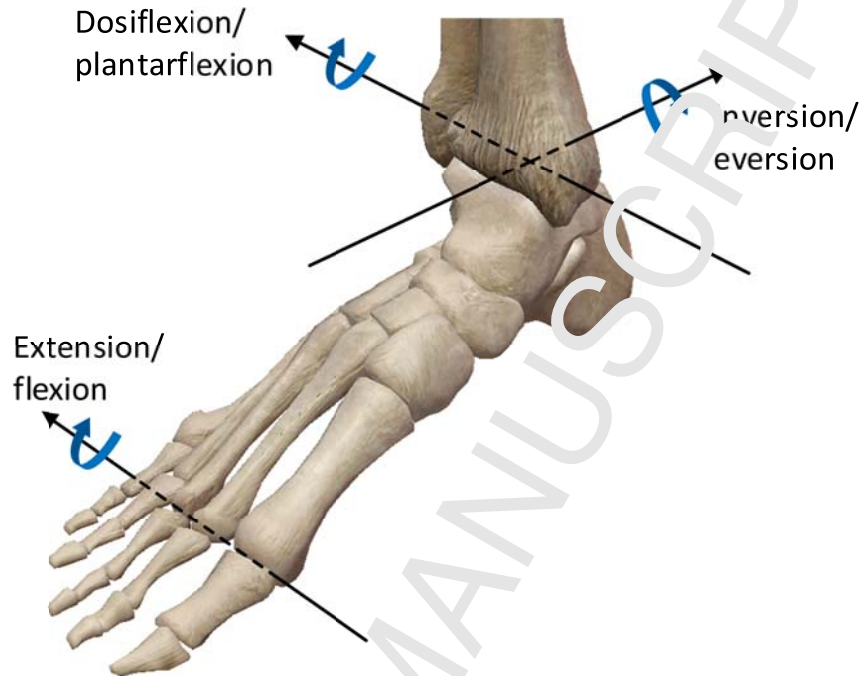


Figure 2. Motions in the ankle and toe joints. The key movements of the ankle joint complex are dorsiflexion/plantarflexion occurring in the sagittal plane and inversion/eversion in the Coronal (Frontal) plane. The major movements of toe joint are extension and flexion.

At initial contact during human walking, the talocrural joint is neutral or slightly plantarflexed. It plantarflexes more before loading response as the foot is lowered to the supporting surface, then dorsiflexes before midstance as the lower leg rotates medially and anteriorly over the supporting foot. During terminal stance and pre-swing, the talocrural joint has large plantarflexion as the body weight is transferred onto the contralateral limb, and it rapidly dorsiflexes to the neutral position immediately following toe-off, to attain toe clearance and then may plantarflex slightly in preparation for next cycle.

The subtalar joint rotates in the whole walking cycle, which influences the weight-bearing alignment of the entire lower body during stance. Similar to the talocrural joint, the motion range of the subtalar joint is small compared with the hip or knee, however it is the indispensable motion that permits humans to adapt to various surfaces. It functions as a mitered hinge to transmit external/internal rotation from the tibia to eversion/inversion about the foot, and vice versa. Since body weight is transferred onto the supporting foot during human walking, eversion of the subtalar joint, as a normal passive response to initial contact with the heel, is one of the motions that absorb shock and prevent injuries. It unlocks the midtarsal joint to produce a relatively flexible forefoot. Meanwhile, subtalar inversion helps to induce foot stability during single limb stance. Maximal subtalar eversion and inversion occur at foot flat in early stance phase and at toe-off respectively.

The key movement of the toe joints during walking are flexion and extension (see **Figure 2**). The toes are off the ground in extension at initial contact, then flex to neutral position from forefoot contact with the ground until midstance. During terminal stance, they extend once again while remaining in contact with the ground, and a maximum of toe extension is reached during pre-swing. The toes flex slightly but remain extension during swing. In the end, a minimal increase in toe extension comes up in preparation for initial contact of next walking cycle. Little or no toe flexion occurs during human walking.

As not all structures and features during human locomotion are dispensable for robot locomotion, only replicating the key relevant features to design a bio-inspired bipedal robot is requisite. Inspired from the basic biomechanics of the ankle-foot complex especially the ankle and toe motion during human walking, we developed a 3D passive dynamic walker with flat feet, toes and ankle spring system.

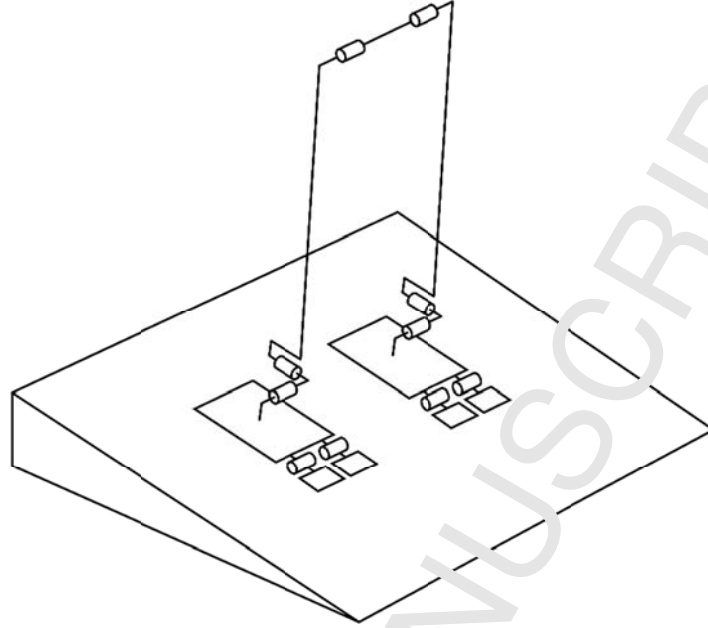


Figure 3. The system configuration of the bipedal walker. It consists of a pelvis, two straight legs, two feet, and four toes with 10 DoFs.

3. Robot Design

The walker (see Figure 3) consists of four main segments (foot, toe, extensible leg and pelvis) and three joints (ankle, toe and hip joints). Each foot includes two toes fixed by steel hinges and plates made of rubber that act as springs forcing the toes to return to the straight position at each step. Each ankle includes a universal joint, four springs and two components made of Delrin connecting the foot and the leg. The telescopic leg links the ankle with the hip, whose extensible feature allows the robot to change the step length, velocity and dynamics of the walking motion.

The robot weights 2.47 kg, and its total height goes from 422.81 to 617.81 mm depending on the setting of its telescopic legs, measured from the highest point at the hip to the ground. The dimensions are based on humans. It is well known that the average human height for men is 176.3 cm which supposes an average leg length of approximately 90 cm and foot size 25 cm leading to a ratio between the leg and foot size of 3.5 [1]. Hence, the height-foot ratio of the robot was designed to consider this value among its different height settings, going from 3.2 to 4.7. However, for passive dynamic walkers, achieving walking stability using human dimensions is quite difficult as they do not have muscles, tendons or any control systems that can provide active stability at every instant. Nevertheless, the design was developed including the extreme positions to test its limit capabilities.

Also, the weight distribution is one of the most important aspects. Based on the Matlab simulation, the CoM (centre of mass) of the robot should be placed at high point to enhance the roll and walking motion down the slope due to gravity. The size of each component as well as the material type plays a key role in the mass distribution and in the final position of the CoM.

The foot is made of aluminium with sufficient strength, weight and high reliability. Each foot was drilled to fix the ankle springs, toes and legs support, and chamfers were fabricated in the edges of the heel, foot sides and toes to improve the contact condition which could enhance the stability and reduce bouncing and perturbations created by the impacts. The leg made of aluminium is adjustable on length by setting the upper part inside the lower part and fixing them together with bolts. The objective of this feature is to change the step length and dynamics in order to achieve a successful configuration as well as allowing the study of their impact on the walking motion. The primary function of the pelvis and the hip joint is to support the weight of the upper body during walking. Since the robot without the upper body

was developed to study the ankle-foot complex of human body, the pelvis was simplified to an aluminium round bar, and the hip joint to a hinge joint with one DoF rather than a ball-and-socket joint with three DoFs minimizing the instability during walking.

Ankle joint. As the main motion in the ankle joint during human walking are dorsiflexion/plantarflexion and inversion/eversion, it could be replaced using a universal joint which permits movements in the sagittal and the coronal plane.

Ankle Springs System. The ankle spring system controls roll and pitch motion of the robot at any instant allowing the legs to swing forward and sideward within a wide range of angles. Stiffness, initial length and elongation are the main factors that affect walking motion. Human muscles do not apply the same forces independently of the walking conditions, but adapt permanently in function of factors such as ground slope, friction coefficient of the surface, weight distribution, activity developed by the human, etc. The spring system acts in the same way and should adopt accurate changes to set the successful adjustments and combinations that achieves walking stability for determined conditions.

The spring system (Figure 4b) was designed to reach a wide range of possible initial spring elongations so that the robot could easily and accurately adapt to different walking conditions. They were selected based on their force-elongation rate to cover the whole robot spectrum of settings. The initial spring length was 63.5mm and their rates went from 1950 N/m to 6670 N/m. Three types of springs with different stiffness (soft, medium and hard) were combined in 4 positions (anterior, posterior, lateral and medial) to study the ankle spring functions (Figure 4a).

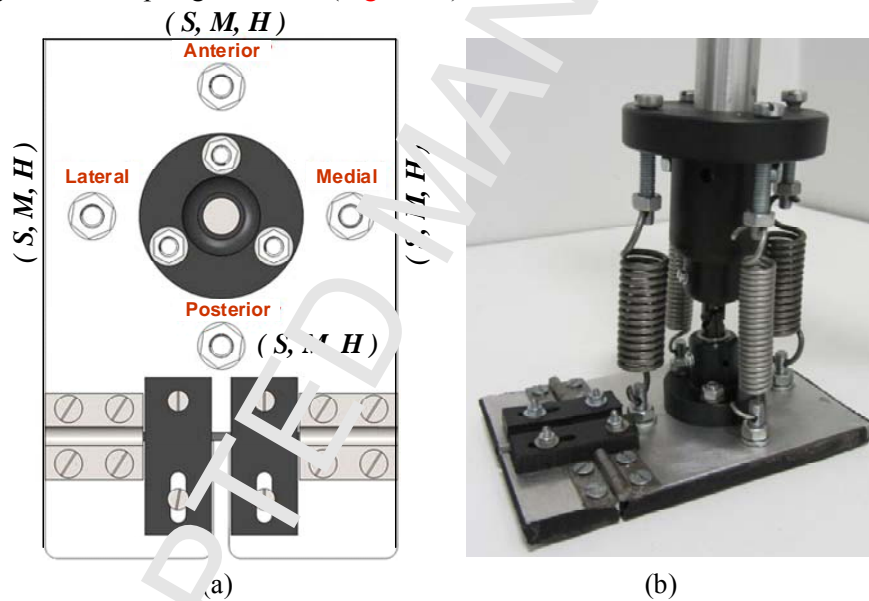


Figure 4. Configuration of the ankle spring system. (a) Schematic of the right foot ankle spring settings with anterior-posterior ankle springs in sagittal plane and lateral-medial ankle springs in coronal plane. Three springs with different stiffness are combined in 4 positions, where 'S' is soft spring (1950 N/m), 'M' medium spring (3260 N/m) and 'H' hard spring (6670 N/m). (b) Real ankle joint in standing position.

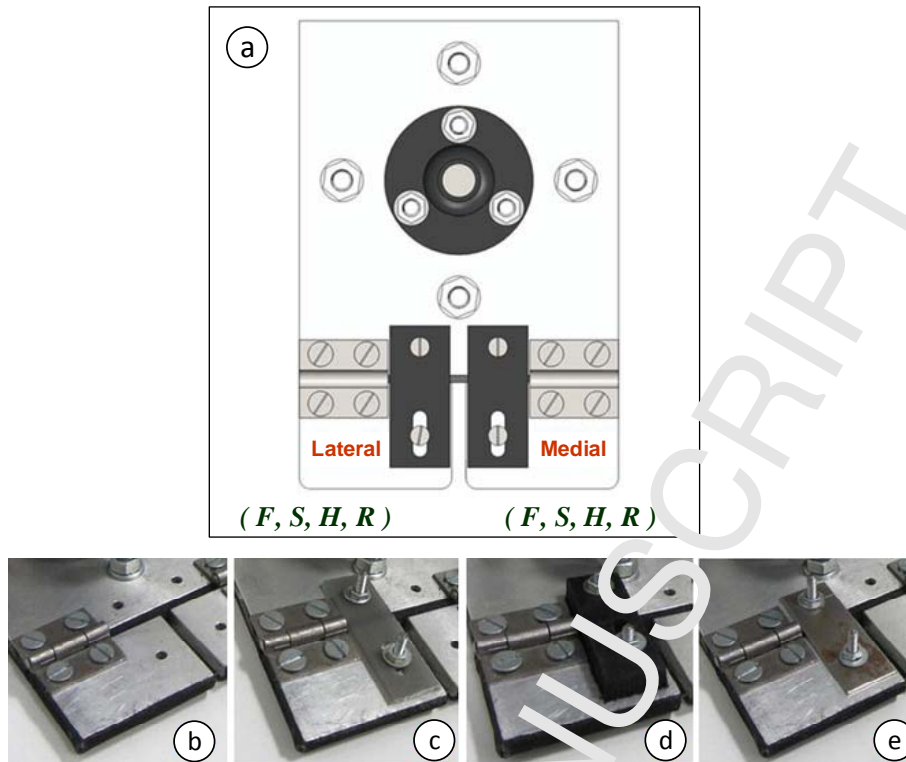


Figure 5. Configuration of the toes. (a) Schematic of the lateral and medial toes settings in the right foot. 4 different toe springs with different stiffness are combined in 2 positions, where ‘F’ means free moving without spring (b), ‘S’ means soft spring (c), ‘H’ means hard spring (d), and ‘R’ means rigid joint without motion fixed with a steel plate (e).

Toes. Two toes pursue to improve the walking stability by increasing adaptability and contact duration between the foot and the ramp. The toes were fixed to the foot by steel hinges placed in the lateral exterior edges of the feet (see Figure 5), which could create sufficient clearance for the elastic rubbers. The elastic rubbers drove the toes to return to the straight position. The elastic rubbers allowed a great variety of strength by changing its thickness or material. In order to validate whether the toes have a real impact on the walking motion of this bipedal robot, the tests include 4 types of toe setups (see Figure 5) with different stiffness.

4. Tests and Results

Although numerical simulation has successfully facilitated the design of 2D passive walkers, 3D passive-dynamic simulation is not as accurate and useful as that of 2D bipeds. There are many uncertain effects in 3D analysis (e.g., collision, rolling, friction and scrubbing torque), that are difficult to characterize and to determine the importance [49]. Simulation sometimes leads to different results in physical robot, such as the *Drift* robot [50] whose swift swing-leg motion cannot increase lateral stability as showed in simulations. Presumably, the instability of numerically predicted 3D biped motion in simulation renders physical realization. Therefore, the robot is studied by a trial and error process testing all the different configurations and analyzing their impact on a real experiment.

Two main tests are pursued in this paper, the ankle stiffness effect based on the spring system and the toes effect on the walking motion. They are studied separately: the ankle stiffness is studied by setting all the different spring configurations, then recording and analyzing the results obtained; the toes stiffness is evaluated based on the best configuration obtained from the ankle spring tests to investigate the real effect of the toes on walking motion. Besides, more tests and configurations have been conducted to study the effect of some specific variables in the walking motion and improve the design for future research.

The robot was tested at two different walking conditions: short step and long step. In general, at the short step condition, the step length is below 7 cm and the robot tends to walk slowly. Whereas during the long step condition, the step length is above 7 cm and the robot moves fast. The different walking

conditions were achieved by initially launching the robot using different methods. The initial launching condition of the robot defines the walking type of the trial.

During tests, the robot motion was recorded by using a video camera at 60 Hz. The number of steps, distance travelled, the total time duration from launching to failure, average velocity and average step length were obtained by analyzing the video frames. The distance travelled was measured from the toes at the initial position to the toes at the last successful step. The total time duration was acquired directly from the video frames. The average step length was calculated by dividing the distance travelled by the number of steps, and the average velocity was calculated by dividing the distance travelled by the total time duration. Unstable motions of the last steps, mainly in the stopping sequence, i.e. very short step of less than 1 cm length, or in the falling sequence, i.e. very long last step just before losing balance, were all excluded when analyzing the video data.

4.1. Variables that affect the walking motion

The robot walking is influenced by various variables that change its movements, velocity, stability, and ultimately its success. It can be assumed as a problem to be solved for each set of determined variables. The variables can be grouped in 3 sets: external, internal and related to the walking motion. External variables are derived from outer elements to the robot, e.g., the slope, friction or damping of the ramp. Internal variables are derived from the robot settings, e.g., the ankle springs, legs length, hip masses. Variables related to the walking motion change the solution to the problem depending on the motion pursued, e.g., walking at a higher velocity and taking longer steps leads to a different setting.

4.2. Preliminary test

Preliminary tests were conducted to determine the optimal leg length and better ground surface enabling the robot walking stably. The robot was tested for each of 13 different leg lengths ranging from 422.81 mm to 617.81 mm. It was found that leg length has significant impact of walking dynamics as it affects the leg mass distributions and also the joint torques. The optimal leg length was found at 549 mm, with which the robot achieved most stable walking motions for both short and long steps. This optimal length was used in the tests investigating the effect of the stiffness of the ankle and toes. Additionally, in the initial tests, the ground friction of the ramp was insufficient, and the robot slipped during walking especially at long steps. Thus, we sanded the ramp surface to increase the ground friction, and successfully solved the slipping problem.

Also, foot soles were designed to reduce the vibrations generated by heelstrike with the ramp. Rubber sheets were fixed to the bottom of the foot, not severely affecting the CoM. They improved the damping capabilities by absorbing the energy released during heelstrike that produced disturbances during walking.

4.3. Ankle test

The ankle spring was tested setting all the spring combinations to find out which performs the most stable walking motion for short and long steps separately. The test was developed based on the best configuration attained during preliminary test, and the toes were equipped with the stiffest rubber.

4.3.1. Ankle spring stiffness.

Three types of different springs were used to test the robot, resulting in 81 configurations to be tested with two different motions, raising the total of 162 testing combinations. For each combination it was launched several times but only taking the first 5 successful ones, and the average of each variable was calculated to be compared with the rest. The measurements for all the launches and configurations can be found in Supplementary Table S1.

The standard deviation of distance travelled for short (Figure 6b) and long (Figure 6d) step walking were computed to show the data variation of each test, which indicates that the following analysis are reasonable as most of deviation value are small compared with the average value of distance travelled.

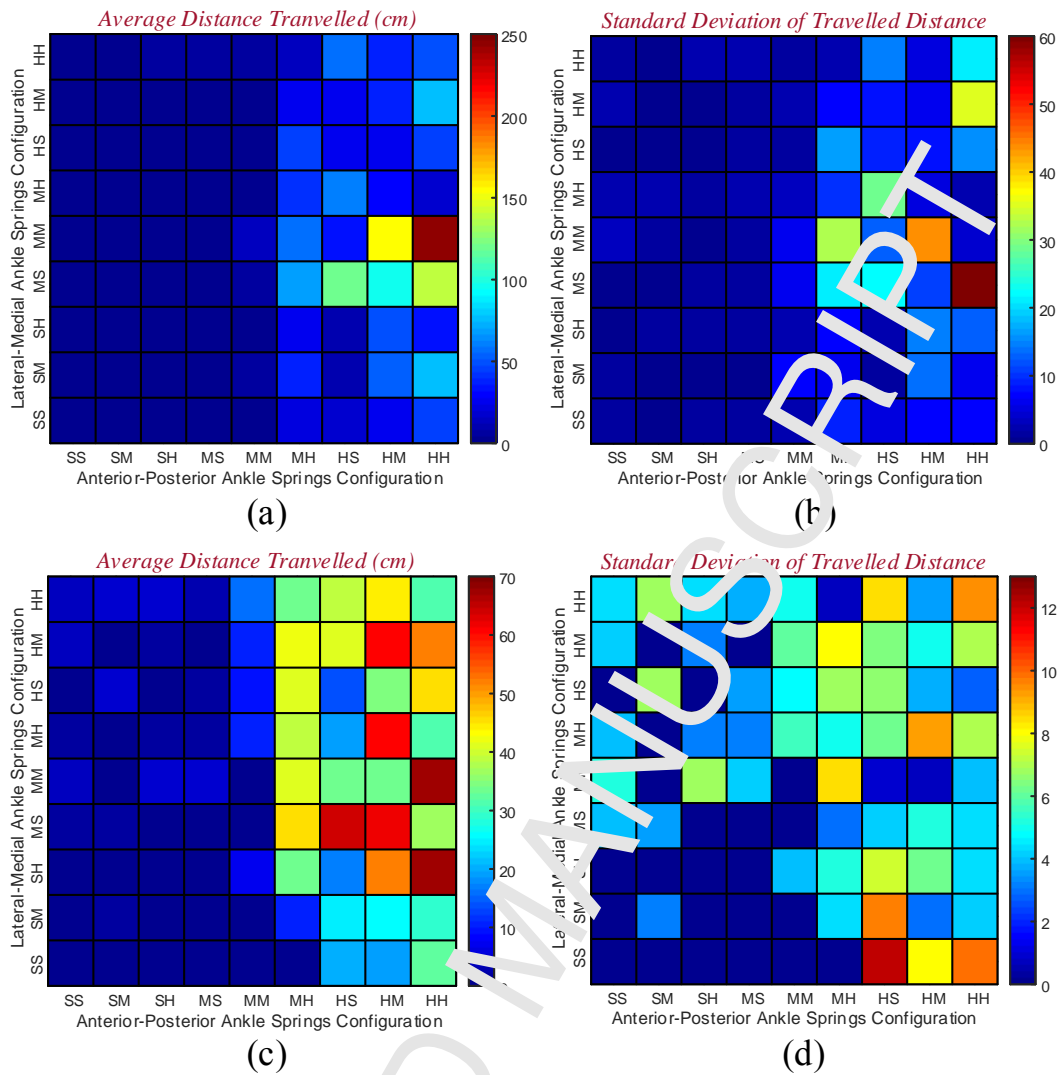


Figure 6. Travelled distance of short step walking (a) and long step walking (c) tests in different ankle springs configuration. For each combination, the mean value of distance travelled was calculated using the data from the first 5 successful tests. The standard deviation of travelled distance for short step (b) and long (d) step walking respectively. S: Soft spring, M: Medium spring, H: Hard spring.

For short steps test, when setting hard springs at the anterior and posterior positions and medium springs at the medial and lateral position, the robot walked the full length of the ramp very stably, and it could keep walking farther, however it reached the edge and fell (see Video 1). The maximum distance travelled was 247 cm, subtracted the foot length 13 cm from the ramp length 260 cm. For long steps test, with the same configuration the maximum average distance was 67.2 cm much lower than short steps.

The results obtained (see Figure 6a and 6c) suggest that once its stiffness overcomes a minimum level, the robot walks steadier for many spring configurations. The main reason to the improvement is the increasing stiffness of the springs placed in the sagittal plane, especially the anterior position. They have a main impact on controlling the pitch motion and avoiding that the robot falls forward or backward. The heavy hip designed to enhance the pendulum motion during walking also makes the robot tend to fall when the stiffness of the ankle is insufficient. **In all the successful tests, the robot can travel more than 4 steps and the spring configurations set at least one hard spring of 6670 N/m which tremendously increases the stiffness of the ankle in its plane.**

Results from short and long steps led to the same conclusion. The test with stiffer spring in the anterior position and soft spring in the posterior position performed successful results, however the case with stiffer spring in the posterior position and soft spring in the anterior position obtained much worse results suggesting that setting stiffer springs in the anterior position can fix instability problems but not the reverse.



Video 1. Successful walking of short steps test with hard springs at the anterior and posterior positions and medium springs at the medial and lateral position.

For the short steps, setting hard spring in the lateral or medial position produced high stiffness in the coronal plane of the ankle leading to a problem called edge treatment, i.e., the raising foot after a very slight inclination from the support leg. Setting medium spring in the lateral and medial position facilitated a decent average of 245 cm travelled distance (see Figure 6a), 5 times more than hard spring. In fact, this difference also occurred in all the testing configured with hard spring of one or two positions in the coronal plane. The average distance travelled for setting at least one hard spring in the coronal plane is 36.23 cm (calculated except the trial of which the number of steps is less than 4). As can be seen in Figure 6a, the best configuration is a symmetric setting with two medium springs in the coronal plane, followed closely by a configuration with a hard spring at the lateral position and a soft spring at the medial position. Setting stiffer springs at the medial position than at lateral led to instability, while testing with two soft springs in the coronal plane obtained the worst results.

For the case of long step walking, the best results were achieved by two configurations, one with a medium lateral spring and a soft medial spring, and the other with two medium springs in the coronal plane (see Figure 6c). The former provided a softer ankle joint stiffness than the latter which enhanced longer steps by performing longer roll rotation cycle that should match a larger swinging of the opposite leg. In other words, setting stiffer springs at the lateral position than in the medial one improved the walking stability.

4.3.2. Step Length and Velocity.

Comparison between short step and long step was analyzed by calculating the average of the most successful short step test and the average of the most successful long step test (see Supplementary Table S1). The short steps test achieve 7.8 times more steps than the long steps test. The distance travelled is also 3.7 times longer than the long step. The step length is increased in 107.8% for the long step leading to a velocity which is 19.5% higher than for short steps.

The configuration with hard springs in the sagittal plane and medium springs in the coronal plane was used to study the relation between the step length and velocity by launching the robot throughout the entire stable spectrum of step lengths. The robot was launched 8 times, each one with a different step length from 3.15 to 12.5 cm, leading to different velocities and number of steps taken (full data can be found in Supplementary Table S2). Figures 7a and 7d show the relationships between velocity and step length, velocity and number of steps respectively at the optimal ankle spring setting. We can see that velocity generally increases with increased step length. Whereas, the number of steps decreases dramatically when walking velocity increases indicating poor stability at high speed. It can be seen from Figure 7a that it is difficult for the robot to achieve stable walking when the step length exceeds 9.50 cm.

Figures 7b and 7c show the average velocities at different ankle spring combinations for the short step and long step tests respectively. Overall, the setting of the anterior-posterior springs has larger effect on walking velocity than the medial-lateral springs. The robot tends to walk slowly with soft anterior-posterior springs. For short step walking, the highest velocity 9.63 cm/s is achieved at spring setting of anterior medium, posterior hard, lateral medium and medial soft. Whereas, for long step walking, the highest velocity 17.10 cm/s is found at spring setting of anterior medium, posterior medium, lateral hard

and medial hard. Figures 7e and 7f show the average velocities at different toe spring combinations for the short step and long step tests respectively. Both medial and lateral toe spring configurations have significant effect on walking velocity. For short step tests, the highest speed 8.81 cm/s occurs when both toes are in free moving (no springs). For long step walking, the highest velocity 14.25 cm/s is obtained when both toes use hard springs.

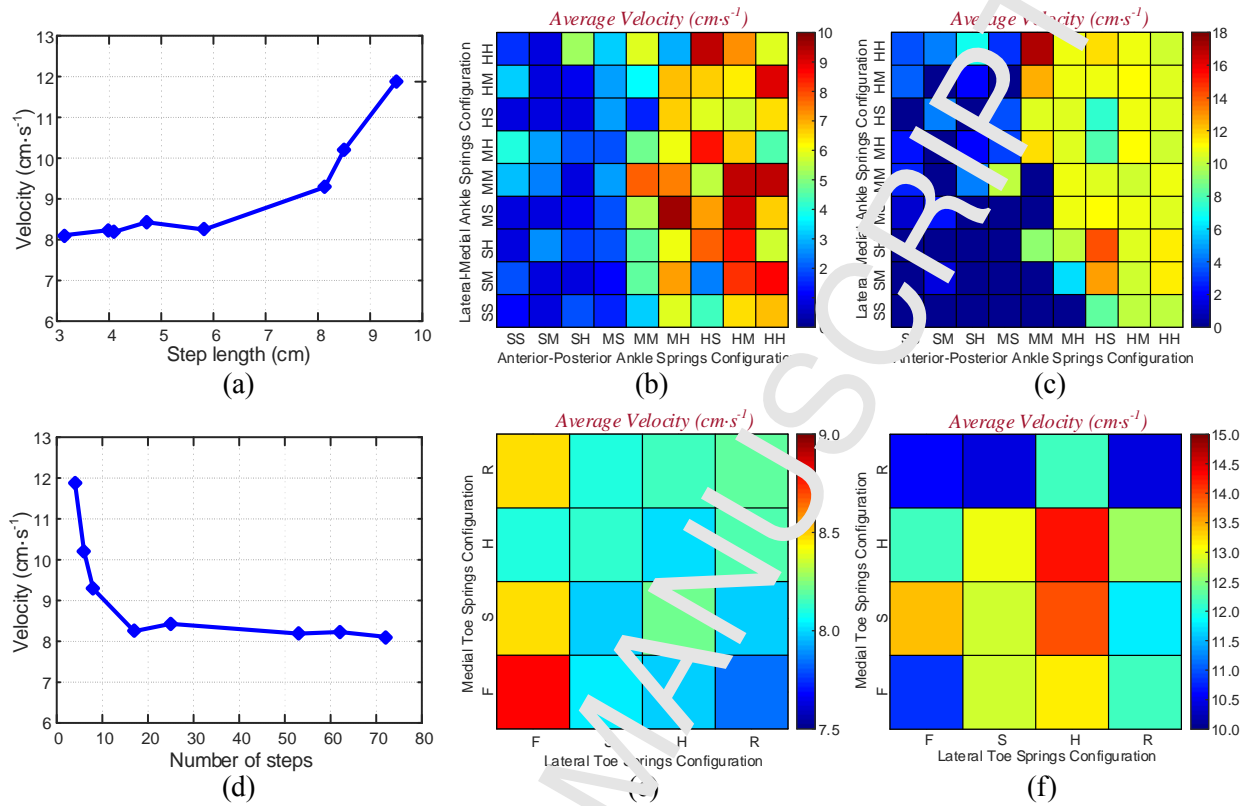


Figure 7. Relationships among velocity, step length, number of steps. (a) Velocity vs. step length at the optimal setting of the ankle springs. The average velocities at different ankle spring combinations for short step (b) and long step (c) tests. (d) Velocity vs. number of steps at the optimal setting of the ankle springs. The average velocities at different toe spring combinations for short step (e) and long step (f) tests. For ankle spring setting, S: Soft spring, M: Medium spring, H: Hard spring. For toe spring setting, F: Free moving (no spring), S: Soft spring, H: Hard spring, R: Rigid connection.

4.4. Toe test

The toes were tested setting all the configurations from the softest to the stiffest with the most successful setup of the ankle spring system which has hard springs in the anterior and posterior position and medium springs in the lateral and medial position. There are 4 different settings for each toe, which makes a total of 16 configurations to be tested for short and long motions, raising the total of 32 testing combinations (each combination is launched 5 times).

The process works exactly in the same way as the ankle springs test. The detailed testing measurements with the entire launches can be found in Supplementary Table S3. The standard deviation of distance travelled for short steps (Figure 8b) and long steps (Figure 8d) walking in different toe settings were computed to support the rationality of the following analysis.

For short steps walking, the results showed similar travelled distance with an aleatory distribution for all the configurations (see Figure 8a), which suggest that the toes have almost no effect on the walking stability. The average number of steps is 59.97 with a step length of 3.98 cm, velocity of 8.12 cm/s and distance travelled of 236.48 cm. The robot could perform very stable walking motion for short steps independently of the toes stiffness but with the normal falling or deceleration.

For long steps walking, the average distance travelled is 55.73 cm with a step length of 8.43 cm. The velocity increases from 4.13 cm/s up to 12.25 cm/s in comparison with short step test, however, taking longer steps entails a great loss of stability decreasing the maximum distance travelled. The robot gets accelerated after 3 steps as the ankles springs cannot control its motion. On the other hand, while the short step test achieves very similar number of steps for every configuration, the results for long steps

present larger variations depending on the toes setting. The toes stiffness influences slightly to the long steps walking, and the robot can travel 18.8 cm longer, which supposes an increment of 40.2%. All configurations that set the steel plate blocking a toe (rigid joint) or allowing free motion of the toe obtained worse results (see Figure 8c). The proper setting of the toes stabilized the robot to walk more 10 to 20 cm distance before falling.

Since the main differences were obtained from cases that blocked at least one toe or allow free motion for both toes, the results were grouped in function of these toes settings. The first group included all the tests blocking the medial toe (rigid joint), the second group blocking the lateral toe, the third group allowing free motion of the toes, and the rest.

Blocking or allowing free motion of the medial toes entailed worse stability (see Figure 8c). When blocking the medial toe with a steel plate, the robot had more difficulties to create sufficient clearance for the swinging of the leg. Also, blocking the medial toe made the foot behave like a unique larger component, and the disproportionate large feet led to problems when swinging forward as they collided with the ground. Indeed, humans with very large foot may have the same problems even if they have knees. On the other hand, blocking the lateral toe did not have the same problem as it can be raised very easily with slight roll angles while the medial toe was still in contact with the ground. When the medial toe was not blocked, the small roll motion required to allow the swinging of the legs facilitated higher stability with the same step length. Therefore, this configuration obtained better results reaching an average of 55.35 cm distance travelled against 49.95 cm obtained by settings with the medial toe blocked.

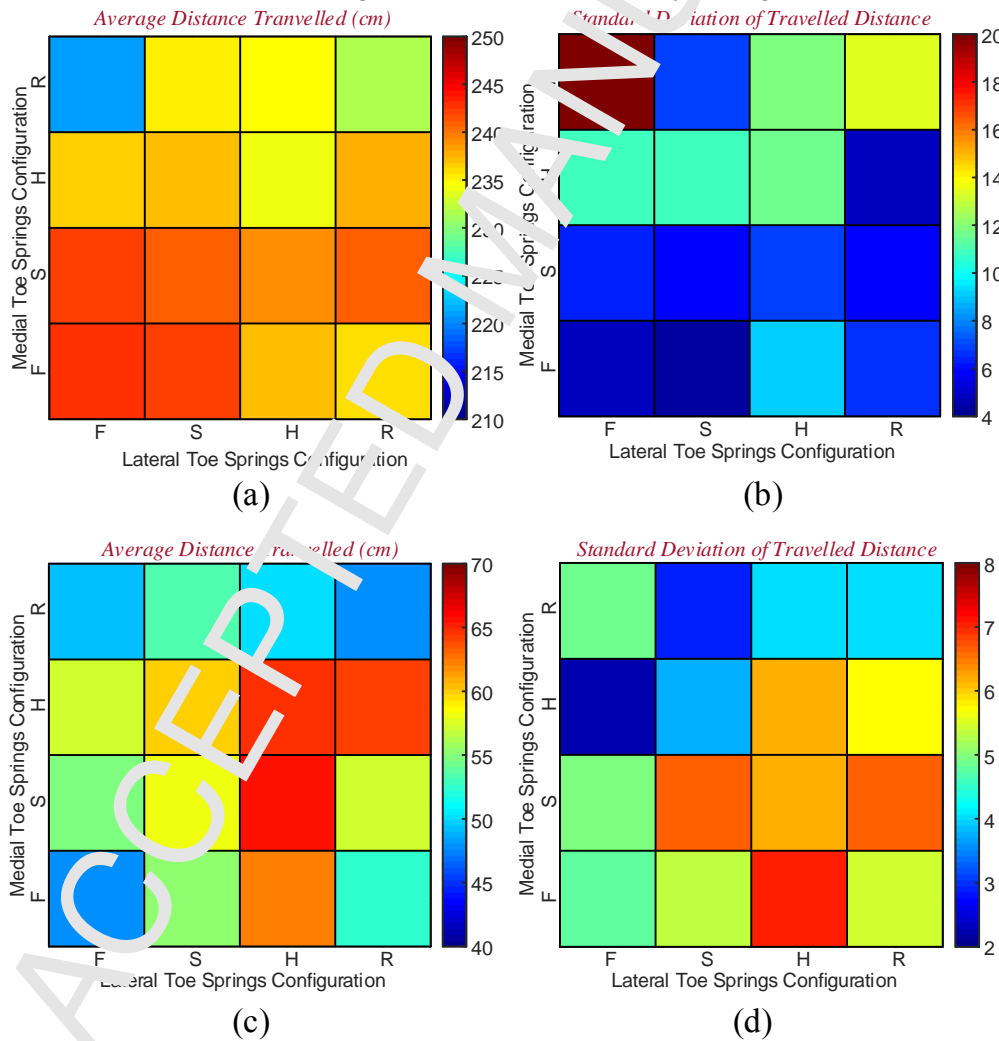


Figure 8. Travelled distance of short step walking (a) and long step walking (c) in different toes configuration. For each combination, the mean value of distance travelled is calculated using the data from the first 5 successful tests. The standard deviation of travelled distance for short step (b) and long step (d) walking respectively. F: Free moving (no spring), S: Soft spring, H: Hard spring, R: Rigid connection.

For test that allowed free motion of the toes, the results obtained were worse (see Figure 8c). When the robot took longer steps with larger roll or swinging motions, the toes stiffness could help to maintain

the stability with more distance travelled. It was observed during testing that when the toes rotated freely about their hinges, the robot lost stability sooner when any of its motions went out of its control limits.

The best results were obtained with medium (soft) and stiffer (hard) rubbers. They allowed the bending of the toes during the raising of the foot and enhanced the stability when the robot started losing the stable motion cycle by providing an extra support.

5. Discussion

It should be noticed that although the conclusions obtained from this bipedal robot may ideally be compared with human walking features, it could lead to error for some aspects as both perform very different walking motions. The fact that humans have knees makes their walking motion very different to imitate. The robot needs roll motion to create clearance that permits the toes to swing forward without colliding with the ground, however, humans do not need such a roll motion as they create clearance by the knee joint. Furthermore, the foot motion is also different as for the robot they land and raise almost parallel with the ramp, while for the humans there is a relative angle with the ground performing a different motion and bending the toes about their joint.

There are 2 main areas of interest to be analyzed in the test of this passive dynamic walker, the ankle spring system and the toes influence on the walking motion. The robot was tested throughout 810 launches for different ankle spring combinations and 160 for toes settings separately.

5.1. Ankle

For the short step testing, the most successful spring configuration achieved very good walking stability obtaining an average of 245 cm travelled distance with 4.18 cm of step length. However, for long step test the robot turned much more difficult to control obtaining only 67.2 cm distance. The robot got worse stability along with increasing step length and velocity, especially when the step length overcame 8cm. The comparison between the most successful results of the short and long step test indicates that the stability of the short steps walking is much higher achieving 7.8 times more steps and 3.7 times more distance travelled than the longer step walking. The step length is increased in 107.8% for the long step test leading to a 19.3% higher velocity. The robot achieved higher velocity taking longer steps but entailing a much higher instability tremendously reducing the number of steps and distance travelled until failure.

The ankle springs have a main impact on the successful of the walking motion. The results suggest that the anterior spring, over any other position, plays a main role providing stability by holding the robot in the upright position and avoiding it from falling forward or backward. It is intuitive thinking that the anterior spring immensely impacts on holding the robot in upright position when walking down the slope, as it tries to recover its free length producing a torque about the ankle which avoids the robot from falling forward. On the other hand, the spring from the posterior position produces a similar torque but in the opposite direction pushing the robot to fall. That is why the entire configurations set the anterior spring with longer initial elongation, i.e., high preload, increasing its force to balance the effect of the posterior spring holding the walker in upright position.

Setting the hard springs of 6670 N/m in the sagittal plane led to the best results, and the springs from the sagittal plane also controlled the pitch angle of the robot which affected its velocity and step length. They determined the position of the massed hips which modified the torques about the ankle joint making the robot walk faster or slower. Successful pitch angles are close to zero. When setting slight larger positive angles, the robot tended to walk faster but leading to higher instability. On the reverse, zero or small negative angles made the robot walk slower and take shorter steps. For extreme pitch angles, the robot tended to fall forward or backward depending on the sign of the inclination. Furthermore, it is very important to place each hip-leg component with the exactly same pitch angle so that both legs have the same velocity and step length, as any slight discordance of their pitch angle would make one leg swing faster than the other resulting in longer steps and leading to instability and failure.

The roll motion was capitolly controlled by the springs from the coronal plane, and a symmetric setting with two medium springs of 3260 N/m attained the highest average travelled distance with great stability, controlled, accurate and repetitive roll motion. Setting stiffer springs at the lateral position than in the medial one led to better results as it enhanced the control of the roll motion by the compression of

the lateral spring acting as a fixed overtravel stop to limit the maximum roll angle and improve the stability. On the other hand, setting the stiffest spring of 6670 N/m in the coronal plane overcame the effect of any other spring placed within its same plane and produced extremely high stiffness leading to problems such as edge tread and instable walking motion. Thus, while the hard spring is beneficial in the sagittal plane to avoid the falling forward, it has a negative effect on the roll motion when placed in the coronal plane.

The fact that the best configuration of the ankle joint has stiffer stiffness in the sagittal plane than the coronal plane can be compared in nature with humans where Tibialis Anterior, Peroneus and Gastrocnemius muscles are much stronger than other muscles around the ankle.

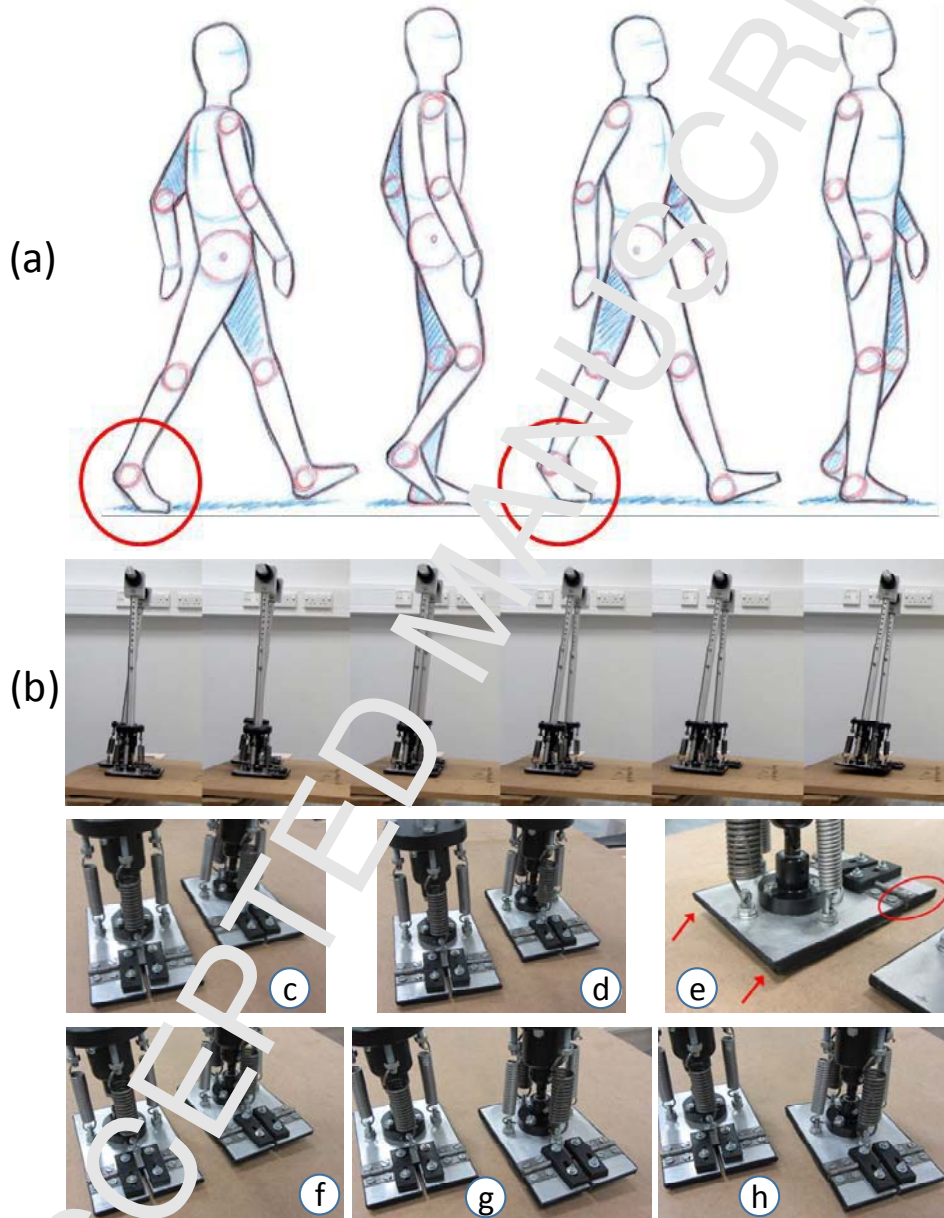


Figure 9. Human and robot walking sequence. (a) Human walks on level ground, where the toes get bended about their joints, from push-off to toe-off until initial swing phase. (b) Robot walks on a slight ramp (5.6-degree tilted). Due to the straight legs without knees, it needs to produce roll motion in order to create sufficient clearance that allows the swinging of the leg, which is obtained by bending the knees during human walking. This feature leads to a very different walking motion and that the robot toes are bended very slightly in comparison with the human ones. (c) The robot in the upright position with 0-degree roll angle, starts getting tilted raising the left foot of the swinging leg. It can be appreciated from (d) and (e) that the anterior edge is raised as well as the lateral edge of the foot; however the medial toe still touches the ramp. After this instant, the whole foot is raised (f) and swings forward (g). (h) Landing of the left foot which is almost parallel to the ramp.

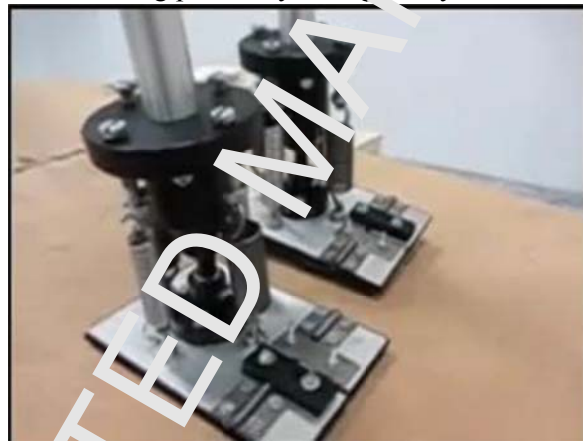
5.2. Toe

The walking motion performed by the robot when taking short or long steps is slightly different changing the toes influence to their respective results. For short steps, the robot performed much smaller roll motion and swinging of the leg, moreover it was slightly tilted backward to reduce torque about the ankle joint produced by the hip weight which would increase step length, velocity, and acceleration. For long steps, its roll motion was larger as well as the swinging of the leg, and the hips were placed slightly forward to increase the trend to walk down the slope with higher velocity and longer steps. These differences in the walking motion make the toes have a different level of impact on the walking stability.

For human walking motion (see Figure 9a), the toes get bended about their joint during walking, especially when the support leg gets behind the body. The robot has a different walking motion. Due to the straight legs without knees, it needs to produce roll motion in order to raise its legs to create sufficient clearance that allows the swinging of the leg. For humans, this roll motion is not needed, and the clearance is created by bending the knees. This feature leads to a very different walking motion and that the robot toes are bended very slightly in comparison with the human ones.

Figure 9b showed that the support foot was raised by the roll motion and the toes were barely bended in the robot. For human walking, the support leg stays behind the swinging one for longer time, increasing their relative angle and forcing the toes to get bended just before raising its foot. Therefore, as longer is the step length, larger is the relative angle between the legs increasing the bending of the toes and the impact of their stiffness in the walking motion.

Due to roll motion performed, the foot does not raise parallel to the ramp making that the medial toe remains in contact and slightly bended while the rest is lifted and pushed to move swinging forward (see in Figure 9c to 9h and Video 2). This condition makes that the medial toe stiffness impacts on the raising of the foot and swinging motion affecting positively or negatively to the stability especially for long steps.



Video 2. Slow motion in the ankle and toe.

For short step test, the step length is so short that the relative angle between the legs is very small and the supporting leg get raised before the toes are barely bended not affecting to the walking motion. Therefore, for short steps the toes have no impact on the walking motion and the reasons for failing are the same ones analyzed above in the ankle test.

For long steps, the toes have a slight impact on the stability of the robot. Blocking the medial toe with the stiffest joint had a negative effect, and it cannot be bended colliding with the ground and impeding an easy lifting of the swinging foot. However, blocking the lateral toe had not such a bad effect, because during the raising of the support foot the lateral toe was lifted first and higher than the medial one counting with sufficient clearance to swing forward without the need to be bent. The most successful results were obtained with the stiffest rubber joint (hard spring) at the lateral toe, and any stiffness option except blocking at the medial toe. Thus, the medial toe could easily be bended to lift the leg and swing forward, and a softer rubber at the lateral position provided more stability when large roll and swinging angles occurred, allowing the robot to travel 10 to 20 cm more distance before falling apart. However, it should be noticed that the positive effect of stiffer toes when the robot starts losing stability getting accelerated and changing its initial walking motion is moderate. They cannot recover the robot from the falling condition, but just avoid falling sooner which leads to travel more 10 to 20 cm distance. More control systems should be researched as combining the right toes stiffness with the proper ankle configuration may make the robot walk stably with long steps and even recover the stability when any of

its motion is out of control.

The fact that the robot has no knees makes the toes influence much lower than expected. The toes permit humans to take longer steps as they remain in contact with the ground providing extra support when the heel has been already raised, which suggests that for knee robots the toes would have a more significant impact in the stability when taking long steps. These statements are obviously based on the robot dimensions, if the toes or foot are much larger with the same robot height, their impact would increase disrupting the walking motion.

Concluding, it is encouraged to develop a robot with knees, flat feet, ankle springs and toes which can demonstrate and reveal biomechanical principles and natures of legged locomotion of human body. The flat feet facilitate the robot to walk more stably, and a larger contact surface with the ground increases the friction which can avoid slipping problems and perform a better walking direction control without bending sideward unintentionally. The ankle springs provide the robot the capability of adapting to perturbances, maintaining the stability and recovering the normal walking motion which would be barely possible for a

robot without ankle joint. The toes enhance the stability especially when taking longer steps providing an extra support and helping to recover the stability when any of its motion goes slightly out of control. The knees would make roll motion unnecessary as the clearance would be created by bending the knee joint. However, this would significantly reduce the complexity of the combined roll and swinging motions but entail new challenges to control the knee motion.

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Appendix A. Supplementary data

Supplementary Table S1. Measurements of all ankle tests.

Supplementary Table S2. Measurements of 8 different step lengths with same ankle and toe settings.

Supplementary Table S3. Measurements of all toe tests.

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HIGHLIGHTS

- A three-dimension passive dynamic walker is developed to investigate ankle and toe function in walking
- The stiffness in the ankle must exceed a minimum level to maintain walking stability
- The ankle joint should have stiffer stiffness in anterior-posterior position than in medial-lateral position
- Adding toes (medial softer than lateral) may benefit robot's biped locomotion especially for longer step length