Novel Tripedal Mobile Robot and Considerations for Gait Planning Strategies Based on Kinematics

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Abstract. This paper presents a novel tripedal mobile robot STriDER (Self-excited Tripedal Dynamic Experimental Robot) and considerations for gait planning strategies based on kinematics. To initiate a step, two of the robot's legs are oriented to push the center of gravity outside the support triangle formed by the three foot contact points, utilizing a unique abductor joint mechanism. As the robot begins to fall forward, the middle leg or swing leg, swings in between the two stance legs and catches the fall. Simultaneously, the body rotates 180 degrees around a *body pivot line* preventing the legs from tangling up. In the first version of STriDER the concept of passive dynamic locomotion was emphasized; however for the new version, STriDER 2.0, all joints are actively controlled for robustness. Several kinematic constraints are discussed as the robot takes a step including; stability, dynamics, body height, body twisting motion, and the swing leg's path. These guidelines will lay the foundation for future gait generation developments utilizing both the kinematics and dynamics of the system.

1 Introduction

STriDER (Self-excited Tripedal Dynamic Experimental Robot) is a novel three-legged walking robot that utilizes a unique tripedal gait to walk [1, 2, 3, 4, 5]. To initiate a step, two of its legs are oriented to push the center of gravity outside a support triangle formed by the three foot contact points, using a unique abductor joint mechanism. As the robot begins to fall forward, the middle leg or swing leg, swings in between the two stance legs and catches the fall. Simultaneously, the body rotates 180 degrees preventing the legs from tangling up.

The first version of STriDER [1, 3, 4] emphasizes on the passive dynamic nature of its gaits. Passive dynamics locomotion utilizes the natural built in dynamics of the robots body and limbs to create the most efficient walking and natural motion [6, 7]. In the new version, STriDER 2.0, all of its joints are actuated for robustness. The inverse and forward displacement analysis is preformed by treating the robot as a parallel manipulator when all three feet are on the ground [5]. STriDER is developed for deploying sensors rather than task manipulations. The robot's tall stance is ideal for surveillance and setting cameras at high positions [1]. The current research focuses on posturing, gait synthesis, and trajectory planning for which the concept of passive dynamics is not emphasized. Since STriDER is a

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non-linear, under-actuated mechanical system in nature (there can not be an actuator between the foot and the ground), the dynamics is a key factor in the planning of gait. Recent research on the optimization of bipedal gait with dynamic constraints includes [8, 9]. The technical approaches intensively discussed in those works can be utilized as the source of reference for the novel tripedal gait in this study. In this paper, we present considerations for gait planning strategies based on kinematics and lay out the foundation and guidelines for future work on a single step gait generation based on both kinematics and dynamics.

2 Background

In this section, the concept of the tripedal gait, locomotion strategies, turning ability, mechanical design, kinematic configuration, and inverse and forward displacement analysis of STriDER are discussed.

2.1 STriDER: Self-excited Tripedal Dynamic Experimental Robot

The design and locomotion strategies of robots are often inspired by nature; however, STriDER utilizes an innovative tripedal gait not seen in nature. Unlike common bipeds, quadrupeds, and hexapods, STriDER, shown in Fig. 1, is an innovative three-legged walking machine that can incorporate the concept of actuated passive dynamic locomotion. Thus, the proper mechanical design of a robot can provide energy efficient locomotion without sophisticated control methods [10]. However, STriDER is inherently stable with its tripod stance and can easily change directions. This makes it uniquely capable to handle rugged terrain where the path planning, turning, and positioning strategies studied here are crucial.

Fig. 1. STriDER 2.0 prototype on right of its predecessor, STriDER

The novel tripedal gait (patent pending) is implemented, as shown in Fig. 2 for a single step. During a step, two legs act as stance legs while the other acts as a swing leg. STriDER begins with a stable tripod stance (Fig. 2(a)), then the hip links are oriented to push the center of gravity forward by aligning the stance legs' pelvis links (Fig. 2(b)). As the body of the robot falls forward (Fig. 2(c)), the swing leg naturally swings in between the two stance legs (Fig. 2(d)) and catches the fall (Fig. 2(e)). As the robot takes a step, the body needs to rotate 180 degree to prevent the legs from tangling up. Once all three legs are in contact with the ground, the robot regains its stability and the posture of the robot is reset in preparation for the next step (Fig. 2(f)) [1, 3].

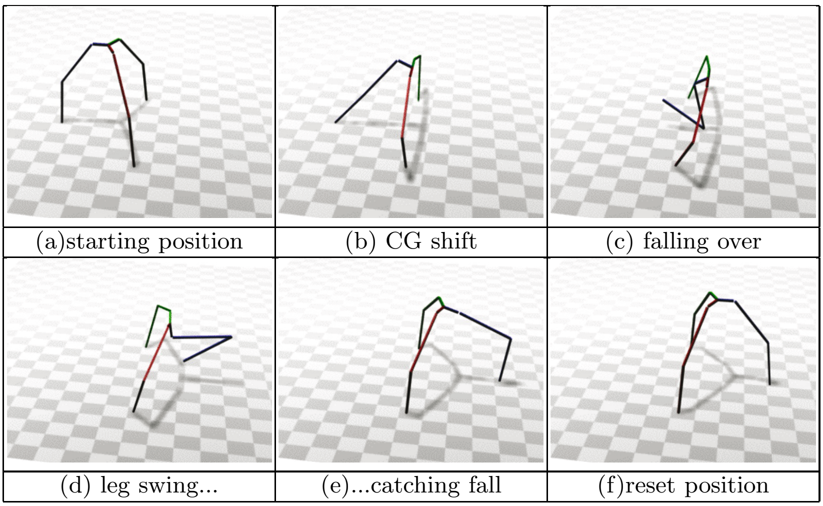


Fig. 2. The motion of a single step [1]

Gaits for changing directions can be implemented in several ways, one of which is illustrated in Fig. 3. By changing the sequence of choice of the swing leg, the tripedal gait can move the robot in 60 degree interval directions for each step [4]. Alternatively, the step direction can be modified such that the stance momentarily changes to an iscoceles or scalene triangle as opposed to an equilateral. This will then change the orientation of the following stance legs from the customary 60 degree angle and therefore the direction of the robot's travel as well. This method is of particular interest because of the inherent flexibility which is more conducive to rugged environments [1].

The design of the first prototype with optimized design parameters for a smooth dynamic gait, and the resulting simple experiments for a single step tripedal gait are presented in [3]. Dynamic modeling, simulation, and motion generation strategies using the concept of self-excitation are presented in [1]. A second prototype, STriDER 2.0, has been fabricated as shown to the right of STriDER in Fig. 1.

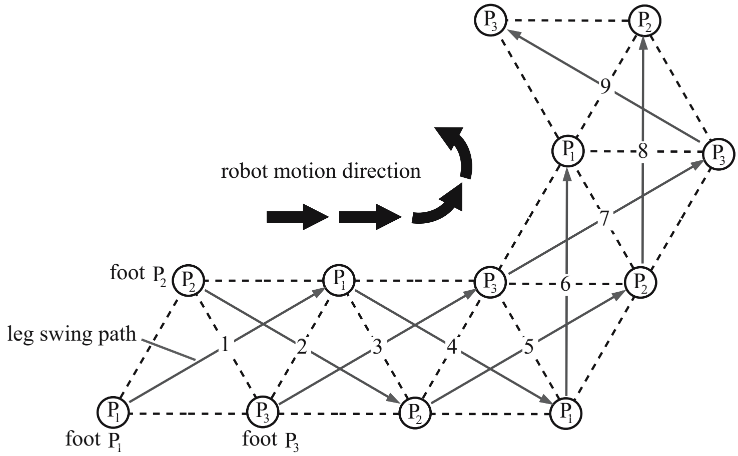


Fig. 3. Gait for changing direction

These models will be used in future experiments to examine STriDER's transitions between gaits, adaptation to various terrains, and stability analysis.

2.2 Kinematic Configuration of STriDER 2.0

The definition of coordinate systems for each leg is shown in Fig. 4. Details of the coordinates frames and link parameters are presented in [5]. The subscript i denotes the leg number (i.e. i=1, 2, 3) in the coordinate frames, links, and joint labels.

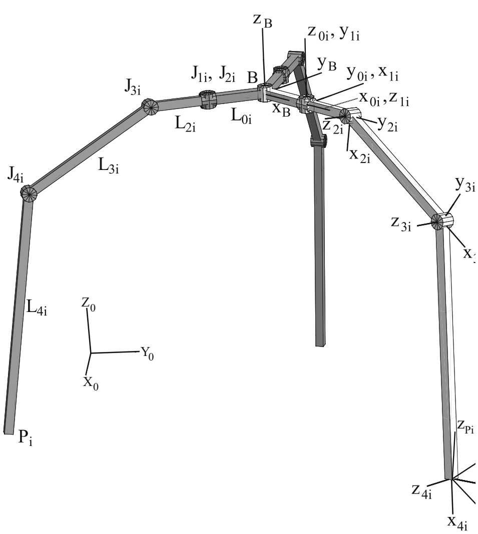


Fig. 4. Coordinate frame and joint definitions [5]

Table 1. Nomenclature

i	Leg number (i=1,2,3)
$\{X_0, Y_0, Z_0\}$	Global fixed coordinate system
$\{x_B, y_B, z_B\}$	Body center coordinate system
J_{1i}	Hip abductor joint for leg i
J_{2i}	Hip rotator joint for leg i
J_{3i}	Hip flexure joint for leg i
J_{4i}	Knee joint for leg i
P_i	Foot contact point for leg i
L_{0i}	Body link for leg i
L_{1i}	Hip link for leg i (length=0)
L_{2i}	Pelvis link for leg i
L_{3i}	Thigh link for leg i
L_{4i}	Shank link for leg i

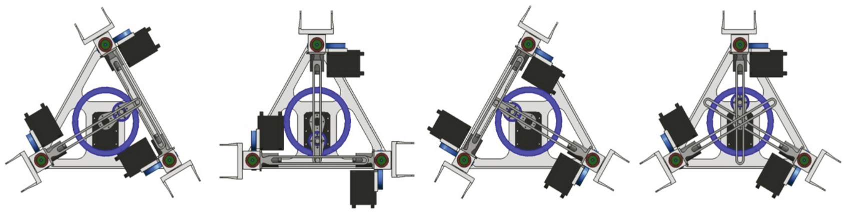
Table 1 lists the nomenclature used to define the coordinate frames, joint and links. A global coordinate system, $\{X_0, Y_0, Z_0\}$, is established and used as the reference for positions and orientations where the negative Z_0 vector is in the same direction as gravity. Each leg includes four actuated joints, J_{1i}, J_{2i}, J_{3i}, and J_{4i}. Because the three abductor joints are actuated together in STriDER 2.0 [2], as described in the following section, J_{1i} is not treated as an active joint in this paper.

STriDER can be considered as a three-branch in-parallel manipulator when all three foot contact points are fixed on the ground. Then the ground is modeled as "the base" of a parallel manipulator, with the body as "the moving platform". The foot can be treated as a passive spherical joint connecting each leg to the ground with the no slip condition assumption. Given the fact that the knee joints, hip flexure joints and hip rotator joints are all revolute joints and each of the three legs mainly has two segments i.e. thigh and shank link, STriDER belongs to the class of in-parallel manipulators with 3 - SRRR (Spherical-Revolute-Revolute-Revolute) configuration. Detailed discussion and the development of the solutions for the inverse and forward kinematics mentioned can be found in [5].

2.3 Mechanical Design of STriDER and STriDER 2.0

STriDER stands roughly 1.8[m] tall with a base that is approximately 15[cm] wide. As stated earlier the leg lengths were determined through an optimization process with consideration for passive dynamic motion. As of now STriDER 2.0 stands only .9[m] tall but this height was chosen somewhat arbitrarily and may change as this version will be used primarily for the investigation of its kinematics as opposed to the dynamics. The body of STriDER 2.0 was designed 18[cm] wide at its base. Both robots are actuated using DC servo motors through distributed control with position feedback.

Because of the continuous inverting motion inherent to the locomotion strategy of this robot, slip rings were built into each of the three rotator joints [1]. It is necessary then to remove the actuator away from the rotation axis of the joint such that wires could be routed through the rotator shaft. In both STriDER and STriDER 2.0 this is accomplished using a spur gear pair [2].



(a) (b) (d) (e)

Fig. 5. The four positions of the rotator joint aligning mechanism with internal gear set

The tripedal gait requires the entire body of STriDER to rotate about the two hip rotator joints of the stance legs as the swing leg swings between them. Since any one of the three legs can be chosen as the swing leg, any two of the three hip rotator joints need to be able to align to each other. The hip abductor joints perform this motion by changing the angle of the hip rotator joints so that the axis of one hip rotator joint can be aligned to another while the third is set to be perpendicular to this axis. In addition to the three orientations in which a pair of rotator joints is aligned, it is also desirable that all rotator axes intersect in the center of the body. In the first prototype of STriDER the three hip abductor joints were independently actuated and controlled with three separate DC motors. While this approach worked, the size and weight of the two additional motors made the design undesirable, as it essentially requires only a single degree of freedom motion to successfully aligning the rotator joints in the four desired configurations.

In [2], a new abductor joint mechanism is presented which aligns the rotator joints using only one actuator which can replace the three motors of STriDER's abductors. This mechanism uses an internal gearset to generate a special trifolium curve with a pin which guides the hip rotator joints via slotted arms through the four specific positions shown in Fig. 5.

3 Gait Planning Constraints for a Single Step

Many factors and constraints contribute to the development of STriDER 2.0's path planning strategies and gait generation. To correctly generate a gait both kinematics and dynamics must be considered. Although dynamics plays a major role in gait generation, the following sections discuss possible considerations for gait planning strategies solely based on kinematics.

3.1 Stability

The robot's static stability is important during a step, as the novel tripedal gait requires the robot to become statically unstable forcing the robot to fall forward and swing its middle leg in between the stance legs and catch the fall. However, when all three feet are touching the ground, the robot must be statically stable by keeping the projected center of gravity point in the support triangle, formed by the three foot positions. Thus, the location of the projected center of gravity point plays an important role in the generation of a gait. A detailed discussion of a quantitative static stability margin is discussed in Sections 4.

3.2 Dynamics

Dynamics plays a key role in producing the gait for walking robots. STriDER can be modeled as a planar four-link invert pendulum in the sagittal plane by treating the two stance legs as a single link connected to the ground by a revolute joint, as shown in Fig. 6 [1]. In this figure, the angle between the link representing the stance legs and the ground is called the tilting angle. Since there is no active actuator between the foot and the ground, STriDER is inherently an under-actuated mechanical system. Assuming no slipping on the ground, the tilting angle during a gait is affected by the coupled dynamics of the other links in the system. The rotation of the body or any of the other actuated links will drive the unactuated links. In [7], self-excited control is utilized to enable a three-link planar robot to walk naturally on level ground. Utilizing this concept of self-excitation, STriDERs passive dynamic gait was produced in [1, 3]. [9] proved the existence of limit-cycle motion of multi-link planar robots by using differential flatness and dynamic-based optimization. This methodology will be utilized in generating the gait for STriDER 2.0 in future research where all of the joints of the robot are actively controlled

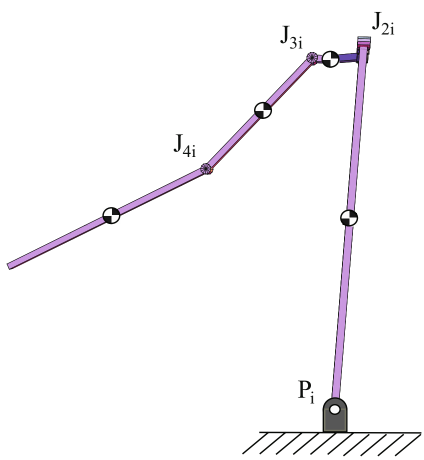


Fig. 6. Inverted four link pendulum [[1, 3]]

to control the unactuated tilting angle of the robot. In this paper, all joint angles of STriDER are calculated based on kinematics only to illustrate the concept of a single-step gait and to emphasize the importance of the kinematic constraints for the system. Future research will address the dynamics of the system together with kinematics considerations developed in this paper.

3.3 Height of the Body

The height of the body must also be considered when taking a step which is defined as the distance from the center of the body (point B in Fig. 4) to the ground in the negative Z_0 direction. The body's maximum height depends on the geometry of the support triangle. Thus, the height of the body when all links of the stance legs are aligned from the center of the body to the stance leg foot position is the maximum height during that step with that specific support triangle's geometry. However, the maximum possible height for any geometry is the total length of the thigh and shank link. The minimum height must allow the swing leg to swing underneath the body as the body rotates 180 degrees without scuffing the ground. The height of the body also affects the speed of the fall. The higher the body the slower the fall of the robot, and the faster the body position is slower the fall of the robot.

3.4 Body Twisting Motion During a Step

During a step, two pivot lines must be considered; one is the pivot line formed by aligning the stance legs hip abductor joints that allows the body to rotate 180 degrees called the *body pivot line*, while the other is the pivot line formed by the two stance leg's foot contact point that allows the entire robot to pivot called the *stance leg pivot line*. When the *body pivot line* and *stance leg pivot line* are parallel while the robot takes a step, the kinematic analysis is greatly simplified and collision between the swing leg and stance legs is prevented. However, for uneven terrains it might be beneficial for the pivot lines to be skewed, as it may aid the swing leg in avoiding obstacles.

STriDER 2.0 has to align two of its rotator joints to prepare for each step. A top view of the support triangle formed by the foot contact points, P_1, P_2, and P_3 is shown in Fig. 7. $\overline{P_2P_3}$ is the *stance leg pivot line* and P_1 is the initial location of the swing leg foot contact point. Line f is formed by points P_1 and P_2 and line e is formed by points P_1 and P_3. Region I is the boundary created between line f, line e and $\overline{P_2P_3}$. For the case presented here, it is assumed that initially, the *body pivot line* is parallel to the *stance leg pivot line* and point P_{12} is the final swing leg foot contact position which must lie in Region I. Since P_1 and P_{12} form a straight line going through Region I, the body has to twist its facing angle and make its projected pivot line perpendicular to $\overline{P_1P_{12}}$. The twisting motion of the body is controlled with the stance legs and during the twisting the plane of the body is parallel with the ground. The twisting angle θ_{TW}, as shown in Fig. 7, is defined as the rotation of the *body pivot line* about its midpoint in $\pm Z_B$ directions, where Z_B is the z-axis of the body coordinate system shown in Fig. 4. θ_{TW} can be determined from the coordinates of P_1, P_2, P_3 and P_{12}, and satisfies the following constraints:

$$-\theta_C < \theta_{TW} < \theta_B \tag{1}$$

$$\theta_A = \theta_B + \theta_C \tag{2}$$

$$\theta_B = ArcTan\left(\frac{\overline{P_3H}}{\overline{HP_1}}\right) \tag{3}$$

$$\theta_C = ArcTan\left(\frac{\overline{P_2H}}{\overline{HP_1}}\right) \tag{4}$$

Note that, θ_B and θ_C are two extreme cases when the final foot position P_{12} lies on line e or f.

The twisting angle of the body is an important factor for the turning strategy of STriDER on various terrains. A large turning angle per step can increase the mobility of STriDER in complicated environments [11].

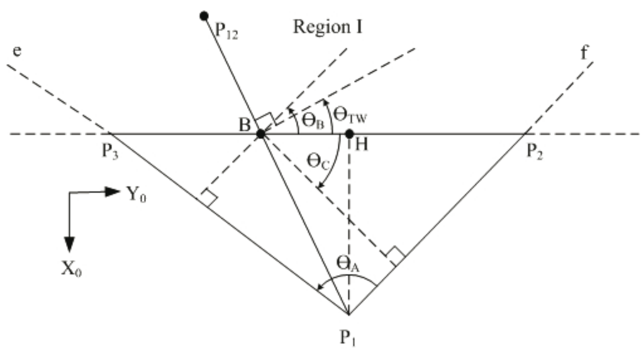


Fig. 7. Top view of the support triangle

3.5 Swing Leg's Clearance and Landing Position

The swing leg's foot path is also an important variable to consider as the robot takes a step. The swing leg's foot should not scuff the ground during the swing portion of the gait, thus the knee must be bent at certain angles to prevent the foot from touching the ground. Also, when considering a single step an allowable region for the subsequent swings leg's foot contact position must be constrained, as mentioned in Section 3.4.

4 Static Stability Margin

A specific quantitative static stability margin (SSM) was developed to assess the stability of STriDER. First, the CG_P point, shown in Fig. 8, is the center of gravity point projected in the negative Z_0 direction to the triangular plane formed by the robot's three foot contact points in 3D space. When the CG_P lies inside the support triangle, the SSM is calculated for a stable condition as shown in Equation (5),

$$SMM = Min\left[\frac{d_1}{r}, \frac{d_2}{r}, \frac{d_3}{r}\right] \tag{5}$$

where d_1, d_2, and d_3 is the distance from point CG_P to each side of the support triangle and r is the radius of the support triangle's incircle, as shown in Fig. 8. The center of the support triangle, labeled I in Fig. 8, was chosen as the center of the incircle of the support triangle since it is the point that represents the maximum equal distance from each side of the triangle.

If the point CG_P lies outside the support triangle the robot is statically unstable, as shown in Fig. 9 . In this case, the static stability margin depends upon the region, defined by the lines connecting point I to the three foot positions, P_1, P_2, and P_3, in which CG_P lies, as shown in Fig. 10.

Therefore the angles, θ_{CG}, θ_2, and θ_3, are defined as that between lines $\overline{IP_1}$ and $\overline{ICG_P}$ and $\overline{IP_1}$ and $\overline{IP_2}$ respectively as in Fig. 10. The static stability margin is then given as Equation (6),

$$SMM = \begin{cases} -\frac{d_3}{r} & 0 \leq \theta_{CG} < \theta_2 \\ -\frac{d_1}{r} & \theta_2 \leq \theta_{CG} < \theta_3 \\ -\frac{d_2}{r} & \theta_3 \leq \theta_{CG} < 2\pi \end{cases} \tag{6}$$

where r, d_1, d_2, and d_3 are defined as before. When the projected center of gravity point, CG_P, lies on any of the support triangle's sides it is marginally stable and the SSM is equal to 0. Table 2 shows the SSM range for these three cases.

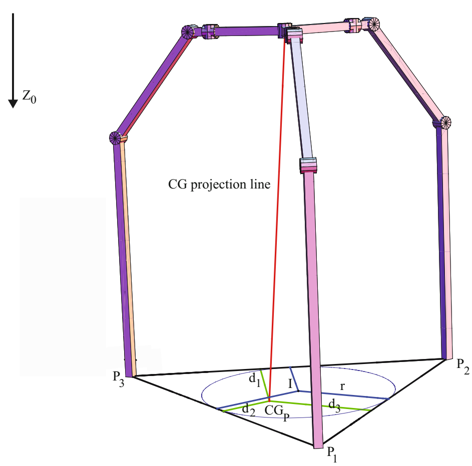


Fig. 8. Stable configuration with SM=0.555

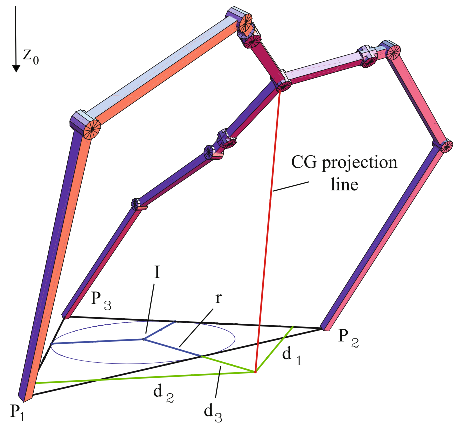


Fig. 9. Unstable configuration with a SM=-0.723

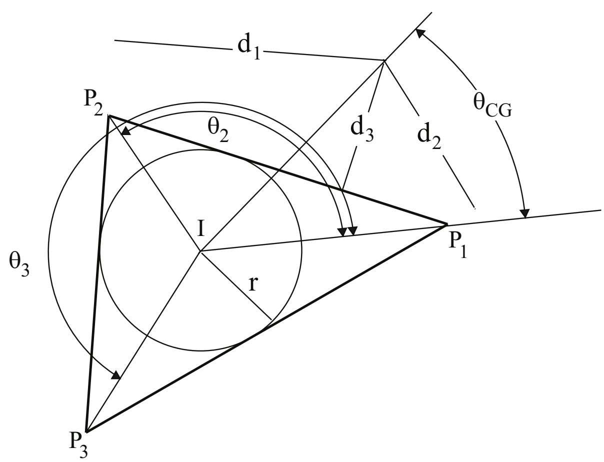


Fig. 10. SSM definition when CG_P lies outside the support triangle

Note, the robot is most stable when the projected center of gravity point lies on point I, thus the SSM is equal to 1. As the point CG_P moves closer to the sides of the triangle the SSM decreases and once CG_P lies any of the sides, the SM is equal to 0. As the CG_P point continues to move further outside the support triangle the SSM increases in magnitude in the negative direction. Fig. 8 and 9 show a stable and unstable case with their corresponding SSM values, respectively.

5 Foundations for a Single Step Gait Generation

This section lays out the foundation and guidelines for future work on a single step gait generation based on both kinematics and dynamics. Several of the

Table 2. SSM Range

Static Stability Condition	SSM Range
Stable	$1 > SSM > 0$
Marginally Stable	$SSM = 0$
Unstable	$-\infty > SSM < 0$

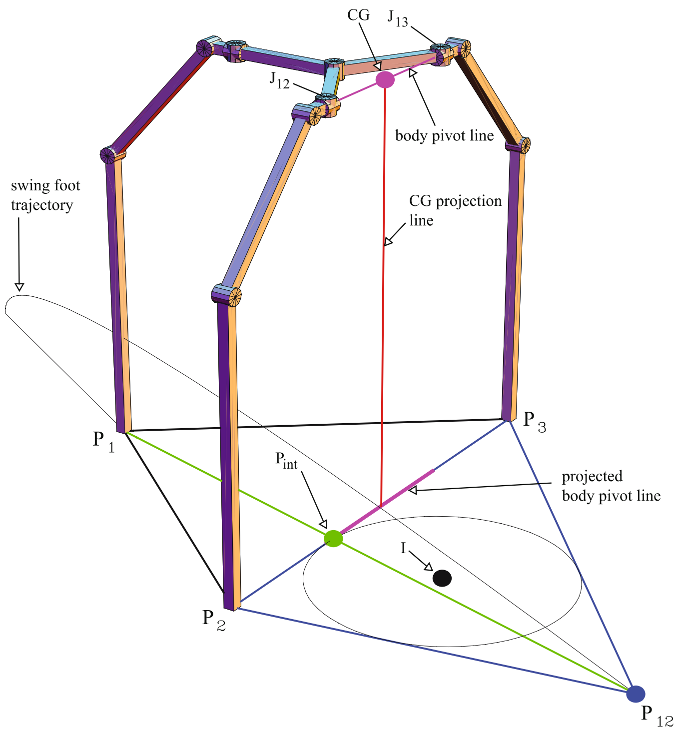


Fig. 11. Gait simulation labels

constraints addressed in Sections 3 should be considered when taking a single step. The objective is to achieve a single step from an initial swing leg foot position, P_1, to a desired final swing leg foot position P_{12} (within Region I), on an even ground, as shown in Fig. 7.

In Fig. 11, the center of gravity can be assumed to be located in the midpoint of the *body pivot line* formed by global positions of the hip abductor joints J_{12} and J_{13}. The swing foot projected path line, $\overline{P_1P_{12}}$, is formulated from an initial swing leg foot position, P_1, to a final foot position, P_{12}. The *stance leg pivot line*, $\overline{P_2P_3}$, is defined as the line connecting the stance leg's foot contact points, P_2 and P_3. P_{int}, is the intersection point of lines $\overline{P_1P_{12}}$ and $\overline{P_2P_3}$.

First, the robot may begin its gait at marginally stable state, where the projected center of gravity point lies on the *stance leg pivot line*, $\overline{P_2P_3}$, as shown in Fig. 11 and discussed in Section 4. The robot must then shift so the projected center of gravity point, CG_P, coincides with P_{int}, the intersection of lines $\overline{P_1P_{12}}$ and $\overline{P_2P_3}$. Then, as mentioned in Section 3.4, the body must twist so the projected *body pivot line* is perpendicular to $\overline{P_1P_{12}}$. The robot is now in position to fall forward and reach its desired final foot location. The rotation of the body or any other actuated links will force the robot to fall forward to initiate the swing portion of the step. Also, the body should be set at a height below the maximum height but high enough so the swing leg would have adequate room to swing in-between the stance legs.

6 Conclusions and Future Research

As an initial investigation, the gait planning strategies for STriDER were studied by discussing several kinematic constraints as the robot takes a step, without dynamic considerations. A static stability margin criterion was developed to quantify the static stability of the posture. Finally, the foundations for a single step gait were presented. Trajectory planning strategies and the generation of optimal gait will be conducted based on both kinematics and dynamics.

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