HUMAN FREE-WALKING MODEL FOR A REAL-TIME INTERACTIVE DESIGN OF GAITS

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Abstract

This paper presents a human walking model built from experimental data based on a wide range of normalized velocities. The model is structured in two levels. At a first level, global spatial and temporal characteristics (normalized length and step duration) are generated. At the second level, a set of parameterized trajectories produce both the position of the body in the space and the internal body configuration in particular the pelvis and the legs. This is performed for a standard structure and an average configuration of the human body.

The experimental context corresponding to the model is extended by allowing a continuous variation of global spatial and temporal parameters according to the motion rendition expected by the animator. The model is based on a simple kinematic approach designed to keep the intrinsic dynamic characteristics of the experimental model. Such an approach also allows a personification of the walking action in an interactive real-time context in most cases.

Keywords: animation, walk, gait, inverse kinematics, biomechanics, personification, behavior, prediction, correction

1. Introduction

Research in Computer Animation tends to be more and more oriented towards animation of complex scenes involving human beings conscious of their environment (Thalmann et al. 1988). This type of animation is multidisciplinary because it should integrate some aspects and methods specific to animation, mechanics, robotics, physiology and artificial intelligence.

In order to create naturalistic human motion, it is essential to take into account the geometric, physical and behavioral aspects. No system based on only one of these aspects can give good results.

To improve the natural aspect of motion, several authors (Isaacs and Cohen 1987; Wilhelms 1987; Girard and Maciejewski 1985; Armstrong and Green 1985; Arnaldi et al 1989) introduce dynamic laws, but generally for simple characters with a few joints because of the important CPU costs of such models.

In fact, the use of a dynamic model requires switching from a problem of specifying positional joint parameters to one of specifying applied forces and torques. This new parameter space is not easier to manipulate. The introduction of inverse dynamics for dynamically processing predefined trajectories does not solve the problem of how to find the natural trajectory for a specified task. This goal may be partially reached by using criterion optimizing methods (energy-based constraints).

Combined with other criteria integrating the physiological limitations of joints, dynamic models may be appropriate for the specification of certain movements: leg balance in walking (Bruderlin and Calvert 1989), hand motion from one location to another (Girard 1989). However, when the motion involves an interaction with the environment (e.g. contact force in a walking action) the expression of such criteria is not trivial and the problem is still open. Moreover, the integration of a personification of motion may satisfy the animator but may be incompatible from a physical point of view. Likewise, results obtained by solving equations may lead to stereotype movements for persons with the same anatomic configuration. Another drawback of dynamic models is the excessive cost in terms of CPU time which prevents the appreciation of the motion in real-time. This is a major restriction for the design of a motion, especially walking which involves expressive information of social, cultural or even behavioral nature.

In this context, we propose a method based on a mathematical parameterization coming from biomechanical experimental data. The main idea of this method is to take advantage of the intrinsic dynamics of the studied motion and extend its application context to a wider range but producing results which are realistic and interesting for the animator. From a taxonomy point of view such a method may be considered as an extension of the traditional rotoscopy method. We are interested in the human walking because of its fundamental importance which also means that numerous studies in biomechanics are available. The main directions of our method are applicable to other classes of human movements more or less complex than walking. The lack of experimental data could seem a serious drawback for these other fields of applications; however, it should be noted that biomechanics has also been involved in other classes of human movement for rehabilitation or sports. Finally, in image analysis, there are research project in automatic determination of temporal evolution of a motion - at the joint level - from a series of 2D images (THEMIS team, IRISA Rennes).

2. Human walking

By definition, walking is a form of locomotion in which the body's center of gravity moves alternately on the right side and the left side. At all times at least one foot is in contact with the floor and during a brief phase both feet are in contact with this floor.

Descriptions of biped gait, and especially human gait, may be easily found in the literature (Inman et al. 1980). In medicine, the problem has been studied for surgery (Murray et al. 1964, Saunders et al. 1953), and prosthetics (Lamoreux 1971). In robotics, much has been written concerning biomechanics for constructing artificial walking systems (Gurfinkel and Fomin 1974, Hemami and Farnsworth 1977, Miura and Shimoyama 1984; McMahon 1984). Several dance notations have been proposed: Benesh notation (Benesh 1956), Eshkol-Wachman notation (Eshkol and Wachman 1958) and Labanotation (Hutchinson 1970) and walking has been described using these notations (Badler and Smoliar 1979; Magnenat-Thalmann and Thalmann 1985).

Finally, several authors (Calvert and Chapman 1978; Zeltzer 1982; Magnenat-Thalmann and Thalmann 1987, Girard and Maciejewski 1985; Girard 1987; Bruderlin and Calvert 1989; Zeltzer 1988) have developed systems for generating computer-animated walking sequences.

As walking is a cyclic activity, we only study the portion of motion between two successive contacts of the left heel with the floor. Fig.1 shows the temporal structure of the walking cycle with the main time and duration information. Fig.2 presents the spatial structure of the same cycle.

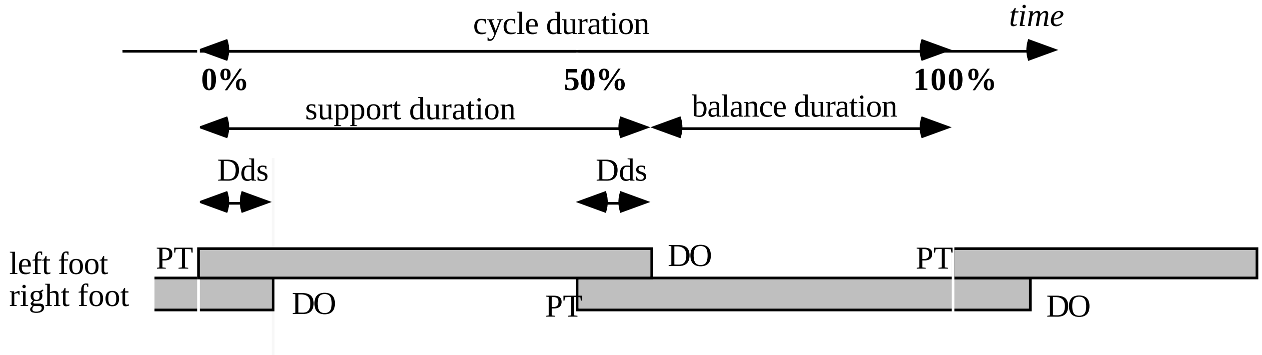

Fig. 1. Temporal structure of the walking cycle
Dc: cycle duration; PT: time when the heel touches the floor; DO: time when the toe leaves the floor; Ds: support duration (duration of contact with the floor); Db: balance duration (duration of non-contact with the floor); Dds: duration of contact of feet with the floor.

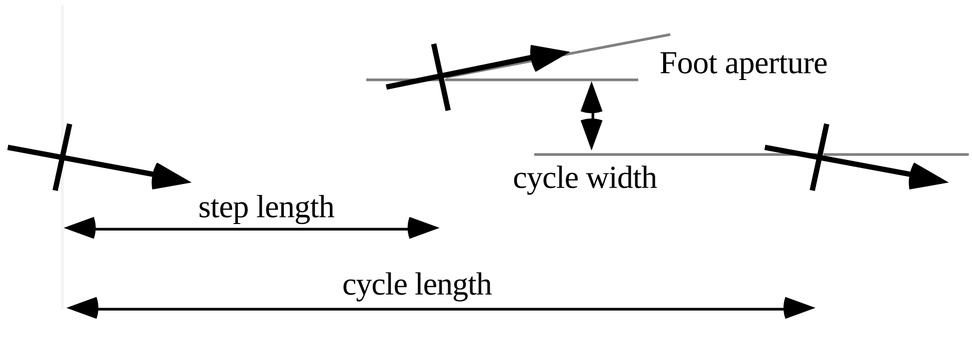

Fig. 2. Spatial structure of the walking cycle

3. The proposed model

3.1 Introduction

The proposed model is intended for producing for any point in time the values of the spatial, temporal and joint parameters of the free walking human being with average characteristics (Kreighbaum and Barthels 1985). All spatial values of the model are normalized by the fundamental characteristic of the walk: the leg length (noted T_j). This is the length between the flexing axis of the thigh and the foot sole, as shown in Fig.3. The average value is 53% of the total height of the human being (Kreighbaum and Barthels 1985).

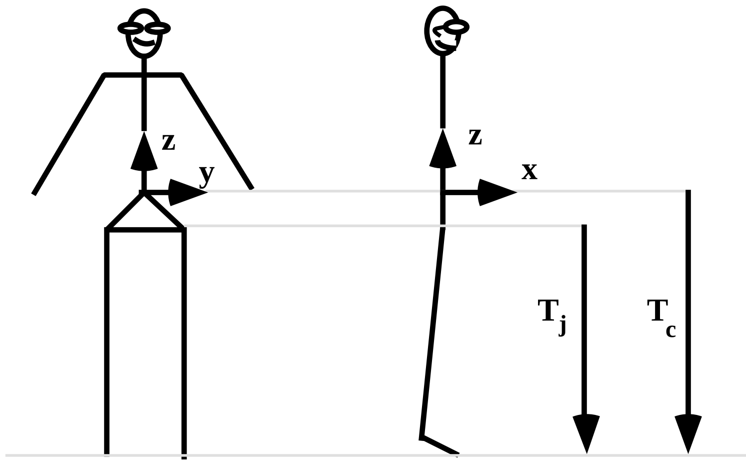

Fig. 3. Definition of the body coordinate system and the initial position

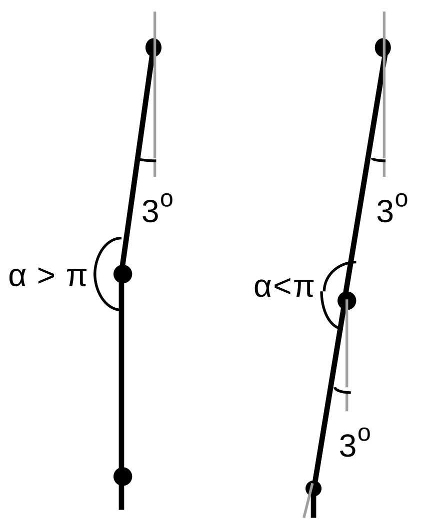

Fig. 4. Stretched and rest positions of the knee

In the following sections, we use the relative velocity, VR, defined as the average walking velocity normalized by T_j. The studies used for designing our model are based on a range of relative velocities from 0.6 to 2.3 (number of T_j/s). Outside this range, we extrapolate the walking towards an immobile attitude corresponding to a rest position of the knee as shown in Fig.4.

3.2 Spatial characteristics

The most important spatial characteristic is the length of relative cycle LcR obtained by a normalization formula from Inman et al. (1981).

$$LcR = 1.346 \sqrt{VR}$$

Two other characteristics are width of relative cycle lcR and foot open angle (in degrees) Op:

$$lcR = 0.02\ VR + 0.05$$
$$Op = -1.4\ VR + 8.5$$

Authors (Murray et al. 1964; Murray et al. 1966) noted a large variation in measures for both these values.

3.3 Temporal characteristics

The fundamental temporal characteristic is the cycle duration Dc, obtained by: Dc = LcR / VR. Murray et al. (1964) have shown that all the other temporal characteristics, the support duration Ds, the balance duration Db and the double support duration Dbs, are linearly dependent on the cycle duration Dc (see Fig.1):

$$Ds = 0.752\ Dc - 0.143$$
$$Db = 0.248\ Dc + 0.143$$
$$Dds = 0.252\ Dc - 0.143$$

All trajectories will be expressed as functions of relative time defined as follows t% = t/Dc.

3.4 Periodic trajectories

Trajectories which will be distinguished are those situating the body coordinate system in the world of joint trajectories internal to the body. The body coordinate system is centered at the spine origin (noted Oc); its orientation is compatible with the main axes of the body at the rest position as shown in Fig.3. The detailed expression of the trajectories is given in Appendix A.

Location of the body in the space: three translation trajectory coordinates situate the body relatively to the position it should have when moving straightforward with the velocity VR.

Vertically: the height of Oc decreases for completing the step. The amplitude of this decrease grows with VR.

Laterally: Oc oscillates laterally in order to ensure the weight transfer from one leg to the other leg. The amplitude is almost always constant.

lead/delay: For an average velocity VR, the body has in fact acceleration and deceleration phases which correspond to the advance to the new step then the stabilization on the new leg. This effect decreases when VR grows because of the smoothing effect due to the kinetic energy.

3.5 Internal joint trajectories

Forward/backward: this flexing movement of the back relatively to the pelvis is done just before each step to move the center of gravity of the body in order to help the forward motion of the leg.

left/right: the pelvis falls on the side of the balanced leg
torsion: the pelvis may rotate relative to the spine in order to perform the step more easily

These three trajectories strongly depend on the individual human being. It is also easy to build a rotation trajectory for the thorax (in opposition to the pelvis torsion) as well as trajectories for the arm motion (in phase with the opposite foot).

The truly walking trajectories are the trajectories of flexing/extension at the thigh, the knee, the ankle and the toe. These trajectories are very similar from one human being to another one on an experimental range of relative velocities. We shall model them using splines (see Appendix B).

3.6 Discussion

We have built a model which may be used at two levels:

- first at a global level in order to generate the average temporal and spatial characteristics (normalized).
- then at the trajectory level in order to describe at each time the position of the body in the space and its internal configuration.

Before going further, let us introduce the concept of virtual floor. This is the plane of the support of the body at the initial position (see Fig.3). When seen from the average location of the body coordinate system during the walk, this plane stays at an invariable height $-T_c$ according to the z_{body} axis. T_c is the origin height of the spine and its average value is about 58% of the total size of the human being (Dreyfuss 1966). It will be useful to consider and to manipulate a virtual floor coordinate system linked to the average position of the body coordinate system.

As the model comes from the synthesis of a large number of experimental data and not from solving motion equations, it is logical to obtain a rather realistic approximation which does not correspond exactly to the support constraint of the virtual floor. This problem may be overcome by modifying the leg flexing using an inverse kinematics method. This method is described in the section prediction/correction. The modification is not important relatively to the general walk motion and we may consider that the degrees of freedom of the pelvis do not intervene in this correction which decreases the dimension of the problem.
Such a method allows a decisive extension of the model to fill the expressive needs of the animator.

4. Extension of the application field of the model

4.1 Spatial and temporal parameters

When strictly applied, a relative velocity, assumed to be constant, completely determines a free walking for a flat floor with a straight direction. However, it is clear that such a context is too limited for an animator who would like to recreate variable situations in space and time. Consequently, we propose to extend this strict context by the following steps:

- provide as entry points the three variables linked by the formula VR=LcR/Dc with the following priorities (see Fig.5):

  - if the relative velocity is specified, it determines the two other variables
  - if only the relative cycle length varies, the cycle duration is fixed and the relative velocity is adjusted
  - if only the cycle duration varies, the relative cycle length is fixed and the relative velocity is adjusted
  - if only the relative cycle length and the cycle duration vary, the relative velocity is adjusted

It should be noted that the three last possibilities cannot be considered as a free walking; the obtained gait is a decelerated or accelerated free gait. The gait is realistic in the neighborhood of the characteristic LcR=f_n (Dc) coming from the normalization formula. Otherwise it will provide a larger parameter space allowing the designer to guarantee a global spatial or temporal constraint. In particular, it will be possible to freeze any motion phase with an infinite cycle duration (in fact, we generally work with the frequency f_c expressed in cycles number/second which is zero in this case).

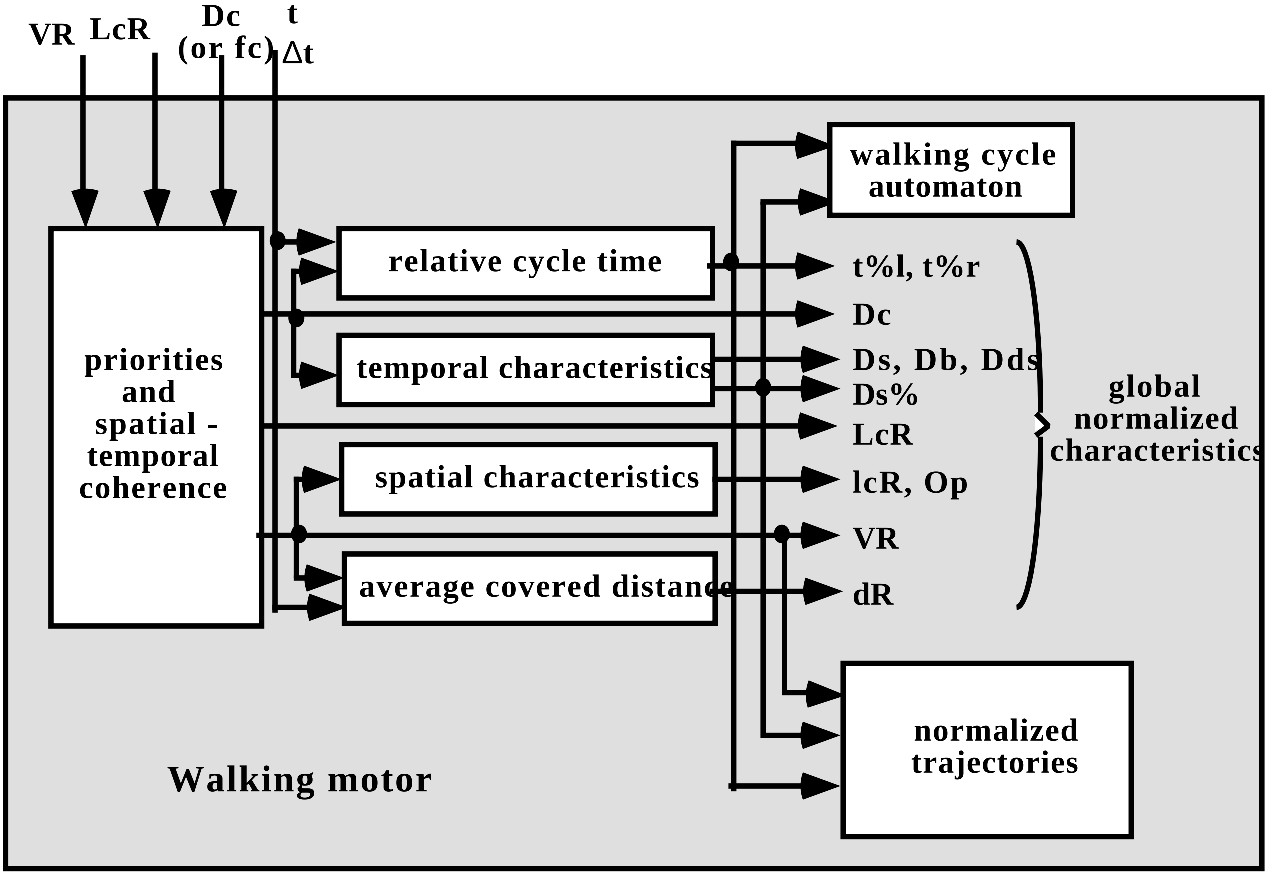

Fig. 5. Walking motor

- allow a continuous variation of the previous entry points maintaining a coherence of the walk. This allows adaptation to an environment which varies fast (e.g. displacement in a crowd)
- project the covered distance by the body at each time onto an independently defined path. VR(t), the average instantaneous relative velocity may be integrated to provide the average relative covered distance. This distance, multiplied by the T_j of the considered human being and projected on the average path, gives us the average location of the body coordinate system in the world, which means the position it would have with a zero velocity. To obtain the exact position, it is necessary to add the instantaneous vector translation dependent on VR and t%.

4.2 Personification

At the present stage, our walk motor may correspond to a wide range of qualitative needs of the animator from three point of views: the general walk function (VR), the attitude (LcR) and the animation (D_c or f_c). However the personification of the motion is intrinsically average and therefore it is necessary to introduce an extra level of individuality.
Our approach to this problem is rather simple but available independently for each instantaneous characteristic (body location and configuration):

$$\text{personified motion} = \alpha \cdot \text{reference motion} + \beta$$

A random perturbation mechanism is also proposed independently for α and β by specifying the maximal amplitude and the smoothing level of a reference noise.

All the parameters of personification should be continuously modifiable and the visual result should be synchronized on the clock model in order to correctly evaluate the design of the personified motion. The continuous variation of the spatial-temporal parameters also allows the designer to fully appreciate the characterization.
Of course, such a freedom for the animator may produce gaits which do not correspond to any free walk: this is our goal. It should be noted that the introduction of the personification does not modify the spatial and temporal coherence (t%, VR) of the initial model. The assumption of the small modifications may be invalidated by the animator's creativity. This suggests that several adaptation methods should be proposed, which will be discussed in the section on prediction/correction.

4.3 Adaptation

Behavior range may become wider by associating constraints to the walk support (foot and by extension shoes). These constraints correspond to a variation between the reality and the imaginary.

Five constraints may be introduced in the increasing order:

1. the support height stays at the virtual floor level
2. the height and the orientation of the support basis are constrained to the virtual floor
3. the support position stays fixed in the world coordinate system of the corresponding virtual floor.
4. the position and the orientation of the support basis are constrained in the world coordinate system of the corresponding virtual floor.
5. the support location is conformed to the world floor (this constraint is under research in order to coordinate walk and vision).

The application of these constraints is driven by the global characteristics of the model. In the case of a very personified gait, the spatial characteristics are generally false and make obsolete the use of the constraints. We propose to fix the value of an average personified velocity, VP, based on the value of the length of an personified cycle LcP. These two values are characterized by the length of the leg T_j and more generally by the given skeleton and its support attributes.

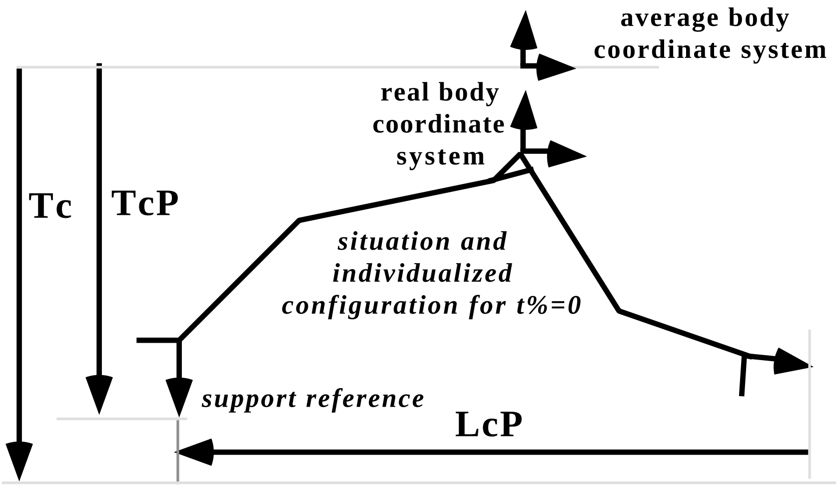

Fig. 6. Personification and adaptation

The value LcP is roughly evaluated as follows (see Fig. 6):

- current personification data are useful to derive the situation and the configuration of the human being for the time t%=0.

- LcP is then approximated by twice the distance along the displacement axis (x_{body}) between the left and right support references.

We have VP = LcP/Dc and the average covered distance dP is obtained by integrating VP(t).

Similarly, a personified height should be proposed for the coordinate system associated with the virtual floor. This value TcP is approximated by the distance along z_{body} between the body coordinate system at an average position and the support reference which starts (see Fig.6).

This primary adaptation guarantees a global spatial and temporal coherence sufficient to apply the constraints. Moreover, we provide two methodologies for following paths: either the animator does not care about the trajectory followed by the body coordinate system or he/she does not care about the coincidence of the virtual floor with a particular world floor. For us, a path is a 3D trajectory associated with a vector defining the vertical direction when it is necessary to define it. A path is private when it is followed by the average body coordinate system. In this case, the height of the virtual floor does not necessarily coincide with a reference linked to the world according to the variations of characterization (T_j, skeleton) or personification (see Fig.7). A path is public when it is followed by the virtual floor coordinate system. A support, linked to the path, is guaranteed for any human being or personification (see Fig.8).

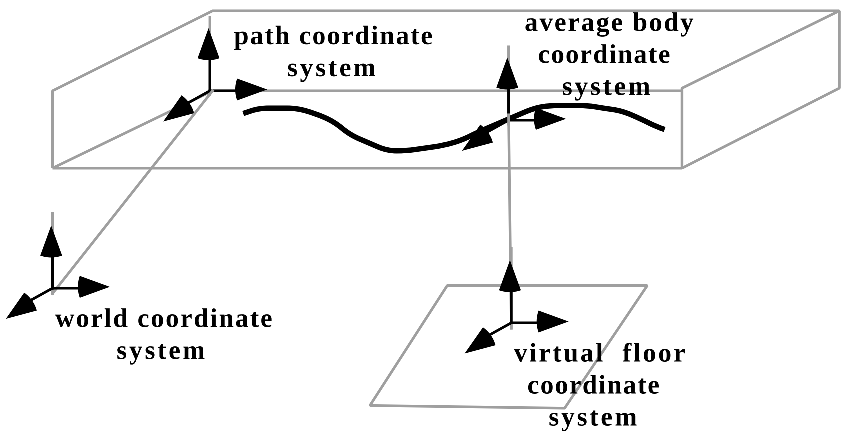

Fig. 7. Use of a private path

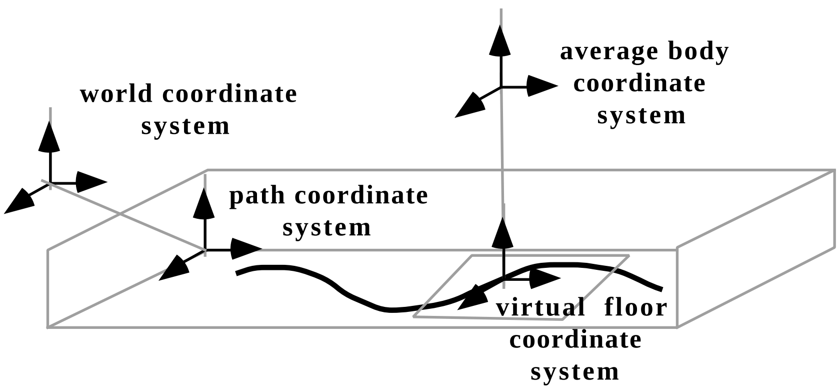

Fig. 8. Use of a public path

5. Functional diagram

The functional diagram (shown in Fig.9) is based on two blocks of prediction-correction which drive the processing of walking at the current time. It also use a module producing the current values of the parameters which are accessible by the animator. This module is strictly limited to predefined and interactive directives. It does not adapt them for a specific task like the adaptation of path velocity in order to lay the foot at specific locations. This is under research, but it should be noted that when the animator may use real-time tools, he/she may interact continuously with the system at a higher level to order a wide range of behaviors.

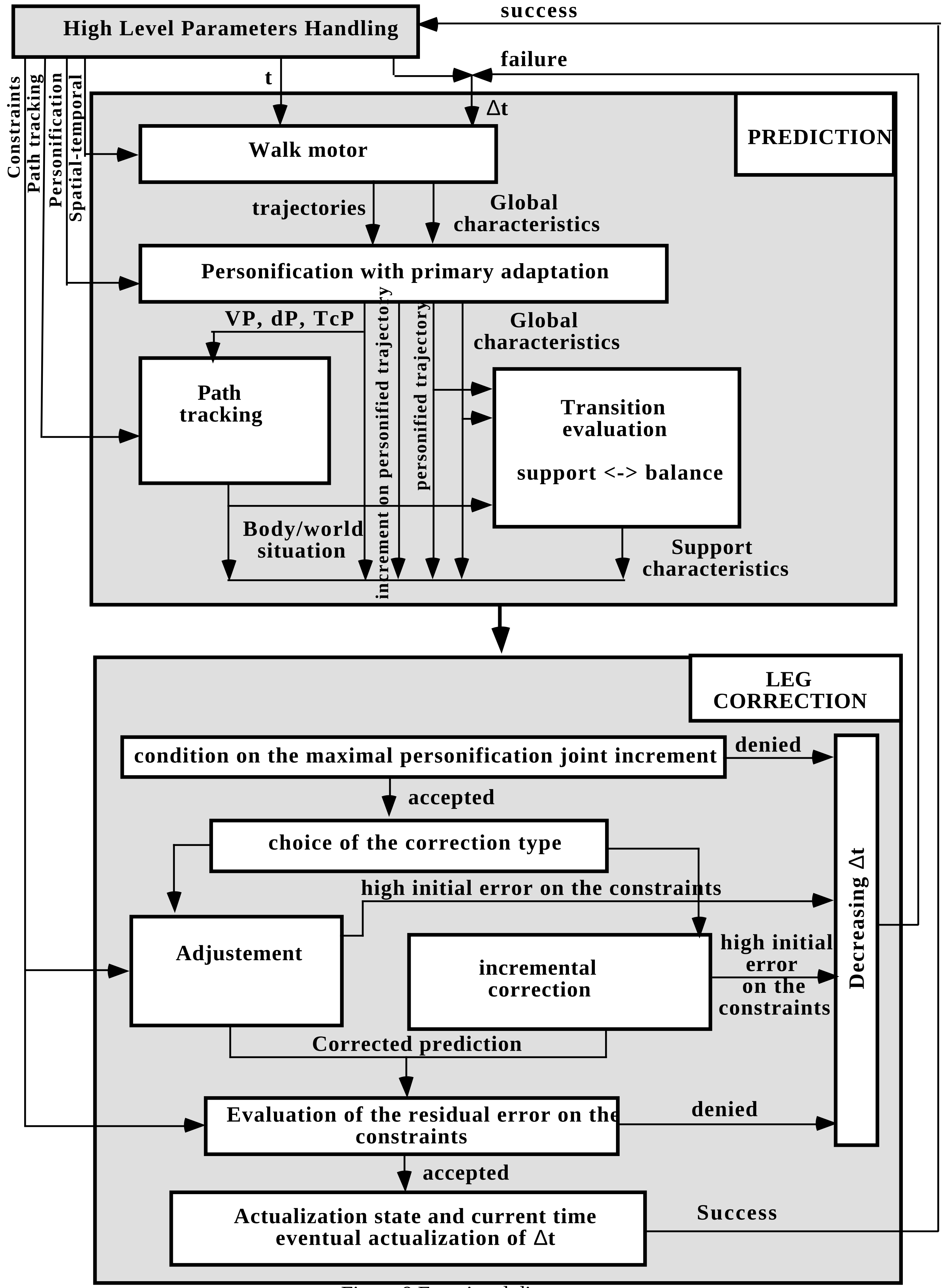

Figure 9 Functional diagram

5.1 Prediction

Prediction provides several levels of sophistication in the design – without constraints – of gaits. The animator may and should work by stepwise refinements.

For the complete case, the process is as follows:

A) The general state is known at the current time tc. This state should correspond to the specified constraints. Otherwise, a method of initial correction should modify it. The state at the time t+Δt now has to be built.

B) The walk motor guarantees the coherence of the spatial and temporal parameters. Other spatial and temporal characteristics may be updated (see 3.2 and 3.3). The average relative covered distance dR(t) is obtained by integrating VR(t). The relative cycle time t%(t) is given by integrating 1/Dc(t). It should be noted that in the restrictive case of free walking, only an analytic expression is known using the normalization formula (extended to variable values):

$$Dc(t) = 1.346.\sqrt{VR(t)}$$

It gives: $t\% = 0.495\sqrt{VR(t)^3}$

For more general cases, a numerical integration is needed.

Trajectories are synchronized using t% for the left leg (t%l), t% for the right leg (t%r) is obtained by a phase displacement of half a cycle.

$$t\%l(t) = t\%(t) \text{ module } [1]$$
$$t\%r(t) = (t\%(t)+0.5) \text{ modulo } [1]$$

Finally, the cycle state is obtained by comparison with Ds%(t) = Ds(t)/Dc(t).

For example, for the left leg:

t%l(t) < Ds%(t) -> left support state
t%l(t) > Ds%(t) -> left balance state

For the right leg, it is similar. Single and double support phases may then be distinguished.

C) Prediction integrates personified trajectories of translation and rotation of the pelvis but not of the legs. In fact, leg trajectories may be unreasonable for the algorithm of inverse kinematics which is then applied. The trajectories have an essential role to play, but not at the foreground. Their personified data have to be integrated into an abstract concept that we call "*coach* legs".

At this stage, leg prediction integrates personified trajectories at t%=0 for the so-called primary adaptation. The integration of the new velocity VP(t) provides an average personified covered distance dP(t).

D) The projection of this distance onto the desired path is immediate. The path is modelled using cardinal splines which have the advantages of passing through the control points. It is then transformed in a sequence of line segments using an adaptative sampling algorithm (Koparkar and Mudur 1983). The incremental process for making correspondence between the curvilinear abscissa with the distance dP is then trivial. We obtain the position of the body coordinate system or the position of the virtual floor coordinate system according to the selected method. The tangent to the curve provides the forward direction (x_{body}). An extra vector (normal to the forward direction) for the vertical locates the set consisting of the body and the virtual floor relative to the path.

E) The last proposed module for prediction determines the areas of potential personification support. Rather than to restrict ourselves to strictly defined phases – which impose constraints on start and end of phases that are hard to maintain – we prefer derive these values of current personification (including *coach*). This requires the specification of one support out of the four proposed: heel, base (linked to the ankle), toe and extremity (linked to the toe).

A support request is created as soon as the reference point associated with a support passes under the personified virtual floor. These requests have a priority which is proportional to the measured divergence. We may of course decide that it is better to assign a mandatory cycle range to the support or the balance. This possibility should be used with care because it may cause totally discontinued transitions.

5.2 Correction

Paradoxically prediction is not strictly defined at the output of this block; this point will be cleared up during the selection of the correction method using inverse kinematics. We briefly summarize this technique.

Our approach to inverse kinematics

The general form of the solution provided by inverse kinematics is often used in robotics (Espiau and Boulic 1985) and Computer Animation (Girard 1989):

$$\Delta\theta = J^{+}\Delta x + (I-J^{+}J)\, z$$

where:

$\Delta\theta$ is the joint space solution of the inverse kinematic problem
J is the Jacobian matrix associated with the main task
J^{+} is the unique pseudo inverse of J and provides the minimum norm solution to achieve the main task
Δx describes the main task to achieve in cartesian space
z describes the secondary task in joint space which is partially achieved on the null space of the main task.

This means that the second term of the solution does not affect the achievement of the main task (z); z is chosen in order to minimize a cost function c such as $z = -\mu \quad c$ ($\mu>0$)

The application of this technique to walking has consisted of a strictly tracking of spatial and temporal trajectories considered as main tasks assigned to feet (or other end effectors) as defined by Girard (1989) or Zeltzer and Sims (1988). An eventual secondary task of optimization of the joint limits may complete the solution (Girard and Maciejewski 1985).

We have chosen a more qualitative specification based on the walk motor. Our main task consists of correcting the motion according to the constraints. The role of the secondary task is to retain the personification dynamic with z proportional to the coach variation.

Two types of main tasks are proposed according to the importance of the joint divergence between, on one part, the leg configuration of the current state and, on the other part, the personification (coach).

If the divergence is low: the prediction is completed by the coach legs and a simple adjustment is made.

If the divergence is important: the prediction is completed by the leg configuration of the current state. The correction integrates an extra constraint of attraction towards the coach leg.

An adaptation mechanism of time increment allows too important corrections or residual errors to be solved.

Finally, the initial correction method is an incremental correction without extra attraction constraint but with the secondary task itself. The correction loop is activated until the constraints are satisfied without temporal evolution.

6. Acknowledgments

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7. Conclusion

We have proposed an important extension of a walking model based on experimental data. The animator may use a wide range of stepwise refinements for the design of real-time gaits. Its major advantage is to allow a qualitative and continuous design of a gait using the dynamic feeling of an experimental model.

The implementation has been carried out in the C language using the Silicon Graphics IRIS 4D workstation. The graphic output shown in Plates 1 to 4 illustrate the personification phase.

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Appendix A: Periodic trajectories of the body and the pelvis

Vertical translation: vertical offset from the average body position expressed in the body coordinate system

amplitude: Av = 0.015 VR

expression: $-Av + Av \sin 2\pi (2\, t\% - 0.35)$

Lateral translation:

amplitude: for VR>0.5 Al = -0.032
for VR<0.5 $Al = -0.128\, VR^2 + 0.128\, VR$

expression: $Al \sin 2\pi (t\% - 0.1)$

a positive value expresses a displacement on the left side of the human being

Translation forward/backward:

amplitude: for VR>0.5 Aa = -0.021
for VR<0.5 $Aa = -0.084\, VR^2 + 0.084\, VR$

phase displacement: $\varphi a = 0.625 - Ds\%$ with $Ds\% = Ds/D$

expression: $Aa \sin 2\pi (2t\% + 2\varphi a)$

a positive value states for an advance relatively to the average position

Rotation forward/backward:

amplitude: for VR>0.5 A1 = 2
for VR<0.5 $A1 = -8\, VR^2 + 8\, VR$

expression: $-A1 + A1 \sin 2\pi (2\, t\% - 0.1)$

Rotation left/right:

amplitude: A2 = 1.66 VR

expression:	$0 \le t\% < 0.15$	$-A2 + A2 \cos 2\pi\,(10/3\ t\%)$
	$0.15 \le t\% < 0.5$	$-A2 - A2 \cos 2\pi\,(10/7\ (t\% - 0.15))$
	$0.5 \le t\% < 0.65$	$A2 - A2 \cos 2\pi\,(10/3\ (t\% - 0.5))$
	$0.65 \le t\% < 1$	$A2 + A2 \cos 2\pi\,(10/7\ (t\% - 0.65))$

Torsion rotation:

amplitude: $A3 = 4\ VR$

expression: $-A3\ \cos 2\pi\, t\%$

a negative value expresses a pelvis torsion towards the left leg

Appendix B: Periodic trajectories of the leg flexing/extension

Trajectories of flexing/extension are modelled using cubic splines passing through control points located at the extremities of the trajectories. The coordinates of these points are noted $(t\%_i, y_i)$ for the control point i. The modelling of the variations of these few points in function of VR is sufficient to rebuild the expected trajectory.

Let consider $h_1(s) = 2s^3-3s^2+1$ and $h2(s)=-2s^3+3s^2$ the two necessary basic Hermit splines.

A trajectory f(t%,VR) with t% between $t\%_{i-1}$ and $t\%_i$ may be for example expressed as follows:

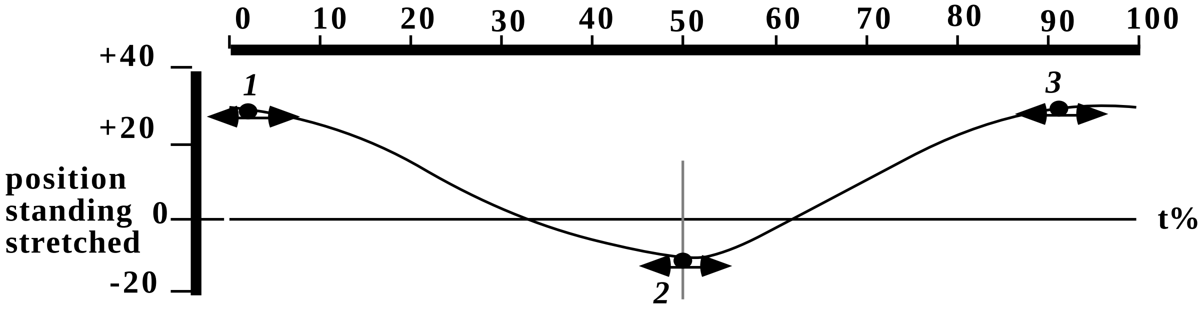
$f(t\%,VR)=y_i+(y_i-y_{i-1})h_1[(t\%-t\%_{i-1})/(t\%i-t\%_{i-1})]$ where the values of $t\%_j$, y_j depend on VR.

The study of the variation of control points in function of VR is performed on the following three ranges:

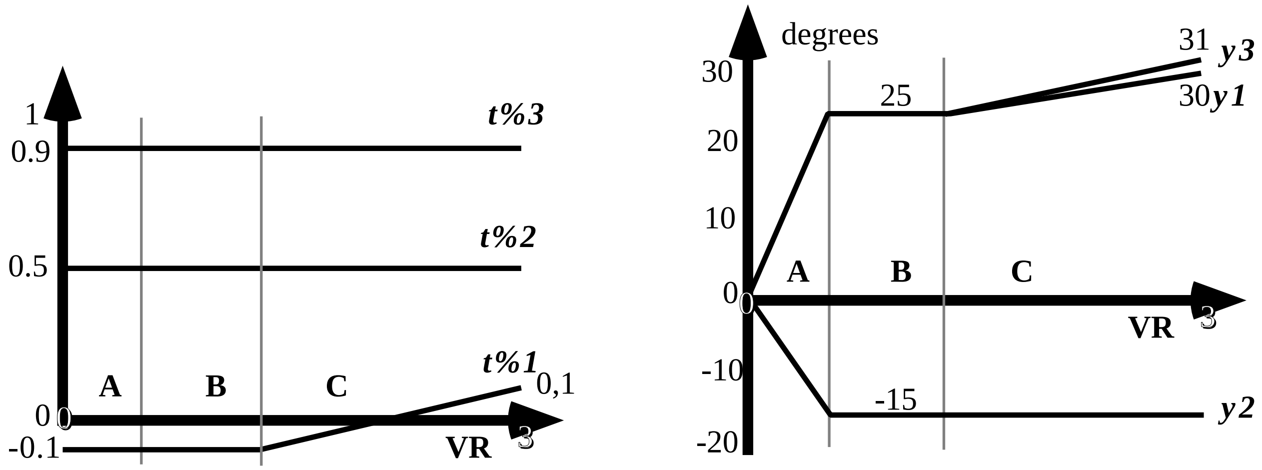
	range	gaits
A	$0 \le VR < 0.5$	starts from the immobile attitude to reach a slow gait
B	$0.5 \le VR < 1.3$	slow gait almost constant
C	$1.3 \le VR <$ upper limit	significant evolution of the gait

B.1 Flexing at the hip

The first figure indicates the three necessary control points. The variation of their coordinates are summarized in the second figure.



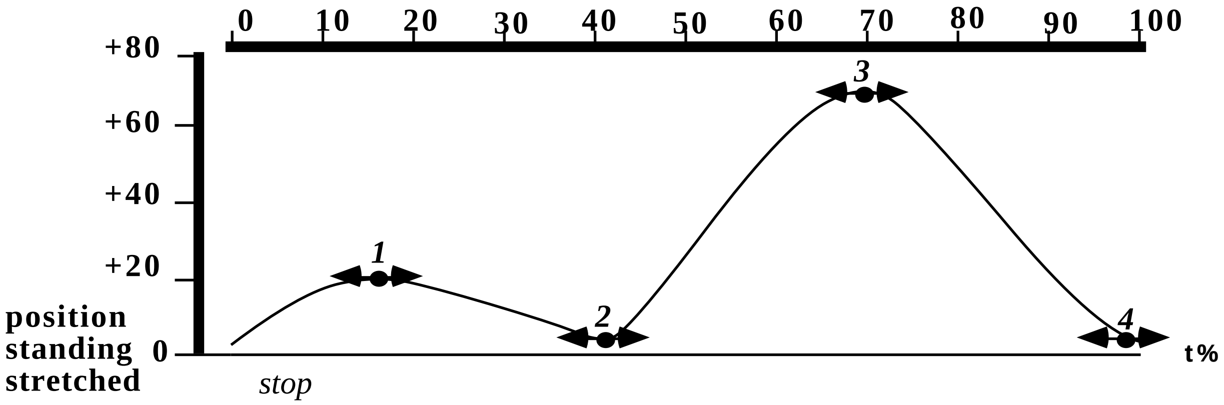
Flexing at the hip



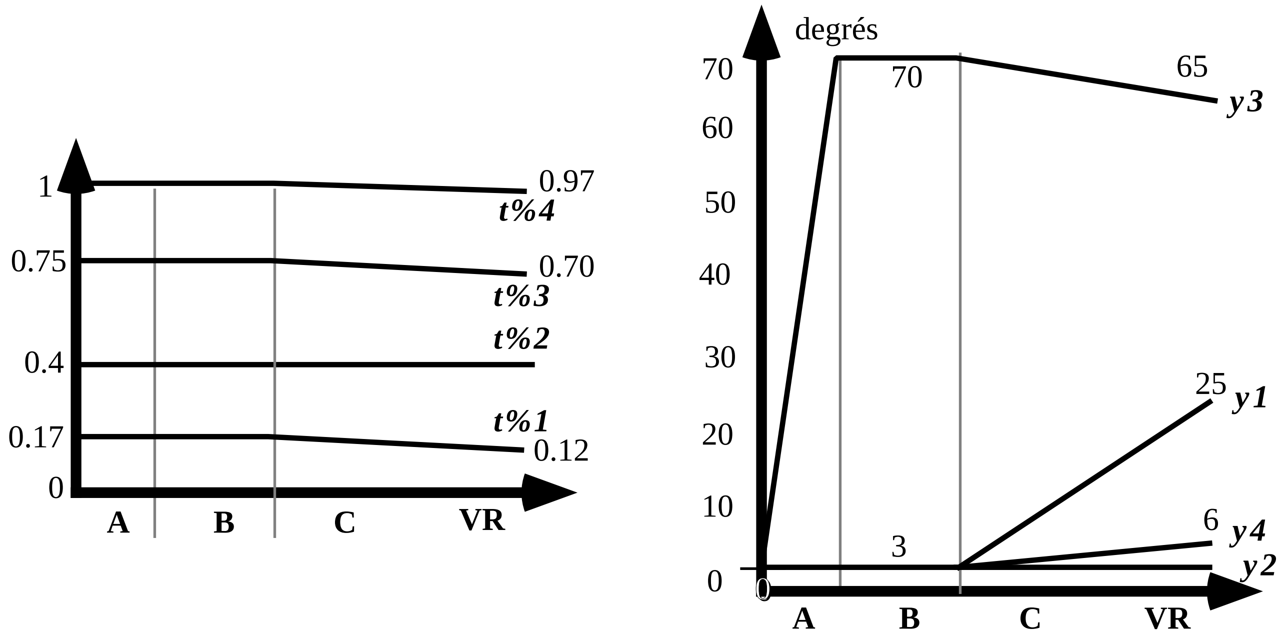
Variations of the coordinates of the control point in function of the relative velocity

B.2 Flexing at the knee

The first figure indicates the four necessary control points. The variation of their coordinates are summarized in the second figure.



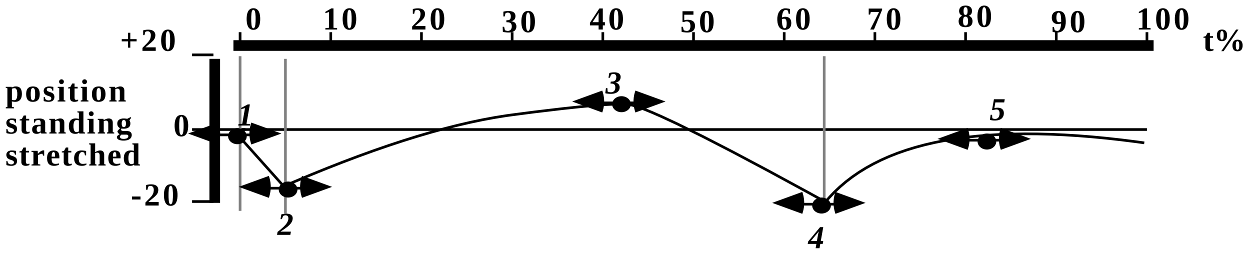
Flexing at the knee



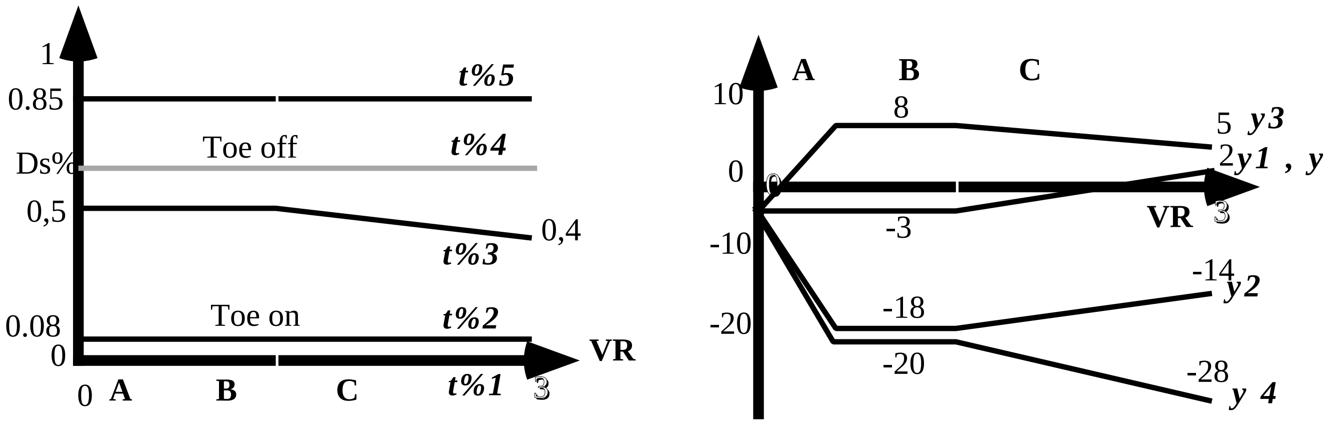
Variations of the coordinates of the control point in function of the relative velocity

B.3 Flexing at the ankle

The first figure indicates the five necessary control points. The variation of their coordinates are summarized in the second figure.



flexing at the ankle



Variations of the coordinates of the control point in function of the relative velocity

The closer a joint is to the floor, the more complex is its trajectory and the more it tends to be modified because of the variation of the floor surface. Consequently, it is useless to model the trajectory of the ankle with great accuracy.

Plate 1: Equilibrium position at the rest (VR = 0).

Plate 2: Beginning support phase for VR = 1.5

Plate 3: Beginning support phase for VR = 2.55

Plate 4: Middle support phase for VR = 0.27

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