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Coach-Trainee : A New Methodology for the Correction of Predefined Motions

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Abstract

This paper presents a new methodology which focuses on the use of Inverse Kinematics to constraint predefined motions while retaining the most of their initial flow of movement.

A general correction method is first presented which emphasizes on the need of two distinct entities called the COACH and the TRAINEE , then a case study of providing floor support to a kinematic model of walking is developed and some general issues for motion specification are considered.

keywords : Inverse Kinematics , motion correction , motion blending .

1. Introduction

One of the current trends in Computer Animation is to try to define a general system which generates motions according to a goal to reach while respecting the general laws of Physics . This is already done when motions obey to goals such as evolving toward an equilibrium state under a gravity force and some others simple attracting forces or torques in joint or cartesian spaces.

The problem is still open for complex articulated structures and complex interaction with the environment . Some current researches have shown the high cost of finding the natural movement to realize a task as simple as moving the hand from one point to another .

This note presents another approach more concerned with efficient and quick specification of complex articulated motions while respecting some geometric constraints. In fact we think that we can get some realistic motions - from an aesthetical and not a physical point of view - by mean of models of specialized motions from biomechanical studies or from rotoscopy or even from a key-framed system (although difficultly). Then two problems arise :

- how to enlarge correctly the scope of such initial sources
- how to blend correctly various sources of motion

Where correctly still refers to an aesthetical judgment of the resulting animation.

The idea is to retain the most of the kinematics of the initial motion - which we now call the COACH - while respecting some geometric constraints to provide a corrected motion which we now call the TRAINEE .

Such a differentiation is needed because the correction method may produce rather distant joint configurations which leads us to retain them in identical but parallel articulated structures.

The next chapters sets the theoretical background of Inverse Kinematics and reviews some of the previous approaches for motion driving. Then our approach is justified from new trends in motion acquisition and design criteria of animation.

A transition function is presented in detail in a one dimensional inequality constraint context. This function is then generalized to deal with one dimensional equality constraints and the complete solution is presented for a multi-dimensional constraint space. A intuitive case-study of a one dimensional inequality constraint is exemplified and applied to a specialized model of human walking. The paper ends with some perspective in motion specification.

2. Theoretical background

The method is a new approach to the use of Inverse Kinematics which integrates within its general solution a way of switching *continuously* to a Direct Kinematics solution.

Considering the problem of achieving a task in cartesian space by driving an articulated open chain controlled with joints, the general form of the solution provided by inverse kinematics is :

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

where:

$\Delta\theta$ is the joint space solution

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 the constraint space (cartesian space)

Δz 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 for any Δz value.

Δz is chosen in order to minimize a cost function c such as $\Delta z = - \mu .\_(c)$ $(\mu > 0)$

Some cost functions have been shown to be interesting in Robotics as maneuverability, avoidance of joint limits , obstacle avoidance with sensors or trying to join a reference configuration (see Espiau & Boulic 1985 for a review).

Animation has also found interesting ways of specifying motions or configurations with respect to goals expressed in cartesian coordinates with Inverse Kinematics.

(see Girard 1989 , Zeltzer 1989, Maciejewski1990) .However in a motion specification context the resulting movement is impersonal due to the minimum norm nature of the provided solution. The addition of a secondary task of joint range optimization doesn't improve this personification aspect of the solution.
Another drawback of this approach is the tedious design of space-time trajectories in cartesian space in order to induce a natural resulting limb motion .

On the other hand, due to the growing research topic of virtual world environment, we believe in a more and more easy way of acquisition of human related motions (data suit). Rotoscopy methods (Ferrigno 1985) are also evolving in the way of automatic analysis of 2D image series to provide joint space trajectories. At last, some good kinematics models of specialized movements can be constructed from biomechanical researches (walking, sports etc).

So what we want now is to use these data for animation ; the major problem is the modelling gap between the human structure whom we acquired the data from and the mathematical structure which will play back the motion. Another discrepancy source comes from a specialized model build from data of statistical nature. But these are only the first coming sources of errors ; we want in fact to enlarge the scope of the initial data by applying them even to caricatural structures or by personifying them in space and time. But as we are distorting the data for aesthetical reasons we do no more respect some natural constraints which we however wish to keep for the same reasons (for example : floor support).

This observation leads us to propose the Coach-Trainee Methodology.

This methodology is based on the use of predefined motions which are corrected by Inverse Kinematics to respect some cartesian space constraints while their kinematics is retained by the secondary task.

As stated before such an approach requires that the mathematical joint structure engaged in the correction splits into two identical but parallel structures :

- the COACH which will retain the initial motion without correction .

- the TRAINEE which will try to follow the COACH but will be submitted to the cartesian space constraints .

In a first guess trial one would think of such a method as a correction of the COACH configuration at each time until it meets the cartesian space constraint and this would be the TRAINEE configuration . For such an approach the COACH-TRAINEE concept is of no need ; a simple correction loop of the initial motion (with adaptative time step or even constant time iteration) is sufficient .

This will provide good results as long as the correction can be done on a one time step process (under the hypothesis of little movements). As soon as large deviations are encountered a proportionally long constant time correction loop is required which is rather costly. The secondary task is then composed of a configuration increment proportional to the gap between initial and current configuration (see Fig 1a). This form of configuration tracking may "forget" the initial COACH kinematics (Fig 1b). Integrating COACH Kinematic information in the secondary task seems useful to orientate the solution toward the next direction but it is difficult in this context due to the possible long length of the constant time correction loop (leading to undesired configurations).

From this first approach we will retain the need of integrating both COACH configuration and Kinematic tracking but in a shorter process of correction .

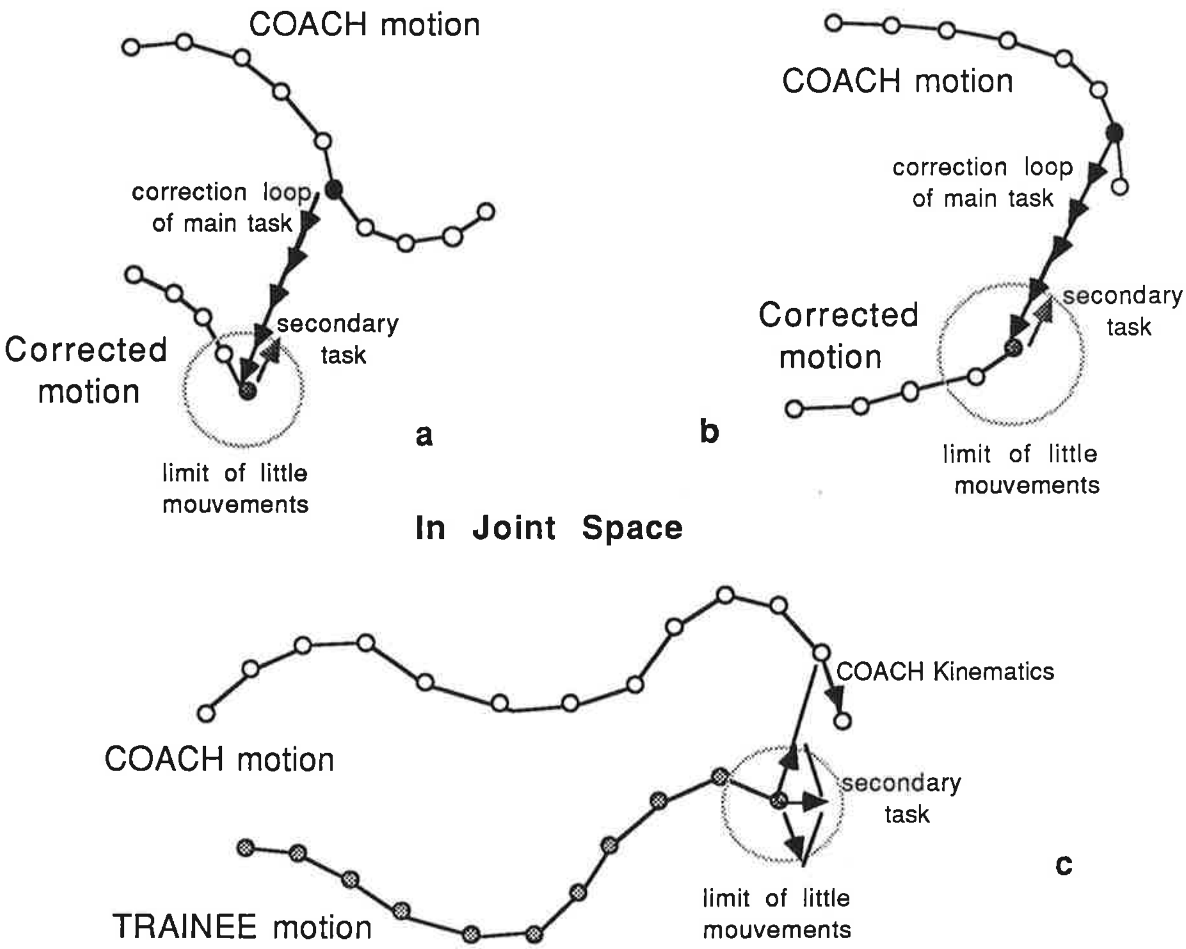

Fig 1 **a/ a simple correction loop with COACH configuration tracking.**
b/ This type of correction loop looses the initial kinematics.
c/ COACH-TRAINEE approach for secondary task.

This is why we introduce the TRAINEE concept for which the constraints are applied to the previous corrected configuration (Fig 1c). This is rather different than correcting the current COACH because we try to keep the most of the former correction process in this way and this normally requires no constant time correction loop. You may wonder to the fact of correcting something which was already corrected on the time before. There are two reasons to do this :

- the previous TRAINEE corrected configuration is related to the global previous state of the animated system which have changed and induced some little deviations to the constraint.

- if the TRAINEE doesn't integrate the current COACH configuration as part of the main task goal how will it return to it if the constraints vanish. A smooth switching from Inverse Kinematics correction to COACH Direct Kinematics duplication is required for an aesthetical continuity criteria .That's why the main task is not restricted to the strict constraint application but prepares the transition from Inverse to Direct Kinematics and vice versa.

In this one step correction process we can now construct the secondary task from both a configuration tracking increment (normalized to little movement limit) and a kinematic tracking increment which duplicates the COACH Kinematics (Fig 1 c).

As the secondary task is only performed on the complementary space required for the constraints achievement we immediately understand that the more the constraint space dimension will be the less the TRAINEE will be able to follow its COACH. The proposed method is mostly interesting for light constraints as inequality constraints or few equality constraints .

3. Scalar Constraint Space General Solution

We first propose the new form of the solution for a one dimensional constraint space :

$$\Delta\theta = J^{+}(f.\Delta x + (1.- f).J\Delta z) + (I-J^{+}J)\,\Delta z \quad \text{with } 0. \leq f \leq 1.$$

A detailed expression of the transition function f depends on the nature of the constraint either equality or inequality but we can already deduce the two extreme forms of the general solution when f is equal to 1. or 0. :

The general Inverse Kinematics solution for $f = 1.$ -> $\Delta\theta = J^{+}(\Delta x) + (I-J^{+}J)\,\Delta z$

The general Direct Kinematics solution for $f = 0.$ -> $\Delta\theta = J^{+}J\Delta z + (I-J^{+}J)\,\Delta z$

$$= J^{+}J\Delta z - J^{+}J\Delta z + \Delta z$$

$$= \Delta z$$

Between those two values is the transition phase where f value is built from the knowledge of two variables :

- how is the COACH relatively to the constraint -> TRAINEE goal.
- how is the TRAINEE relatively to its goal -> TRAINEE deviation

3.1 Inequality Constraint Transition Function

We rather present the form of f in the inequality constraint case which is more intuitive.

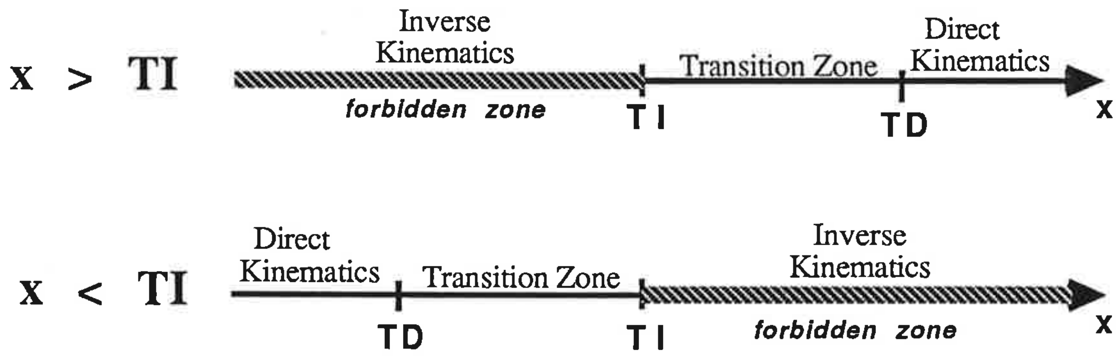

Fig 2 : Inequality Constraints with Transition Zone

The transition function can have many forms but we have chosen a parametric cubic function which provide continuity of the first derivative.

Let us call x the unique dimension which is constrained and xc , xt the respective COACH and TRAINEE variables. We also need two constant values to define the transition zone between Inverse (TI) and Direct (TD) Kinematics threshold (Fig 2).

The proposed function deals with inequality constraints of the form (Fig 2) :

xt >= TI (if TI = Min) or xt <= TI (if TI = Max)

Then we define four internal variables which are :

Min = minimum (TI , TD)
Max = maximum (TI , TD)

Trans = SD - SI

signe = 0 if Trans = 0.
= 1 if Trans > 0.
= -1 if Trans < 0.

Normalized TRAINEE goal -> Tg

xc <= Min	Tg = 0.
xc >= Max	Tg = 1.
Min < xc < Max	Tg = (xc - Min) / Trans

Normalized difference between TRAINEE goal and Inverse Kinematics limit -> d

TD > TI	d = Tg
TD < TI	d = 1. - Tg

So $d = (1. - \text{signe})/2. + \text{signe} \cdot Tg$

Normalized Deviation between TRAINEE goal and TRAINEE situation -> D

$$D = Tg - (xt - Min)/Trans$$

Signed Normalized TRAINEE Deviation relatively to the Inverse Kinematics limit -> Δ

$$\Delta = \text{signe} \cdot D$$

In Constraint Space

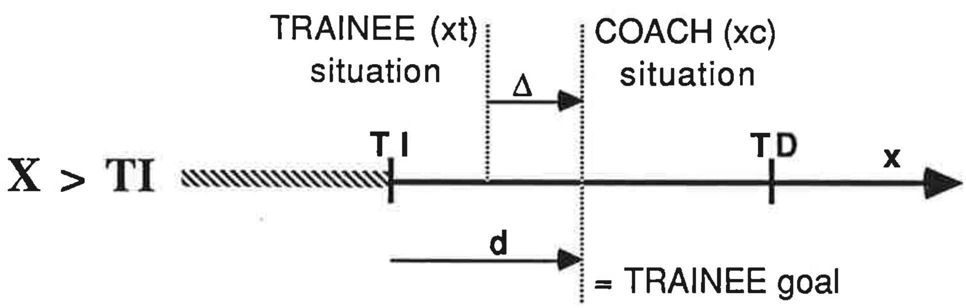

Fig 3 : Illustration of the transition function variables

Transition Function f (d,Δ)

The general form of the transition function is then :

if	$\Delta < 0.$ and	$\Delta <= 1 - d$	f = 0.
if	$\Delta > 0.$ and	$\Delta >= d$	f = 1.

else

$$f(d,\Delta) = [-2.]\Delta^3 + [3.(2.d - 1)]\Delta^2 + [-6.d(d - 1.)]\Delta + [2.d^3 - 3.d^2 + 1.]$$

The figure 4 shows the transition surface created by the variation of both d and Δ .

We illustrate this choice of transition function with the case x > TI (see Fig 3) for which d = Tg and Δ = D .

In this case as long as the COACH is under TI the TRAINEE is assigned TI as a strict goal to reach with Inverse Kinematics.

As soon as the COACH goes beyond TI the TRAINEE goal follows it until it reaches the SD limit (calculation of d).

In this transition zone another component is inserted within the main task expression : it's part of the secondary task weighted by a (1. -f) coefficient while the tracking of the TRAINEE goal is weighted with a f coefficient.

This weight takes into account how the TRAINEE is situated with respect to its current goal (calculation of Δ):

- The nearer of TI the TRAINEE is the more the TRAINEE goal tracking is weighted (positive values of Δ). This explains the upper limit for which f remains to 1.

- On the other hand if the TRAINEE is situated on the other side of its goal with respect to TI then the TRAINEE goal tracking is symmetrically less weighted (negative values of Δ). This explains the lower limit for which f remains to 0. .

Finally for any constant value of d the function f is a cubic step going :

from 0.	for $\Delta = d - 1.$
to 1.	for $\Delta = d$

3.2 Equality Constraint Transition Function

A first proposition suggests that Such a constraint can be built from two Inequality constraints which do not overlap but it creates some ambiguity as soon as the COACH is between the two Direct thresholds. This must be solved by the current TRAINEE situation.

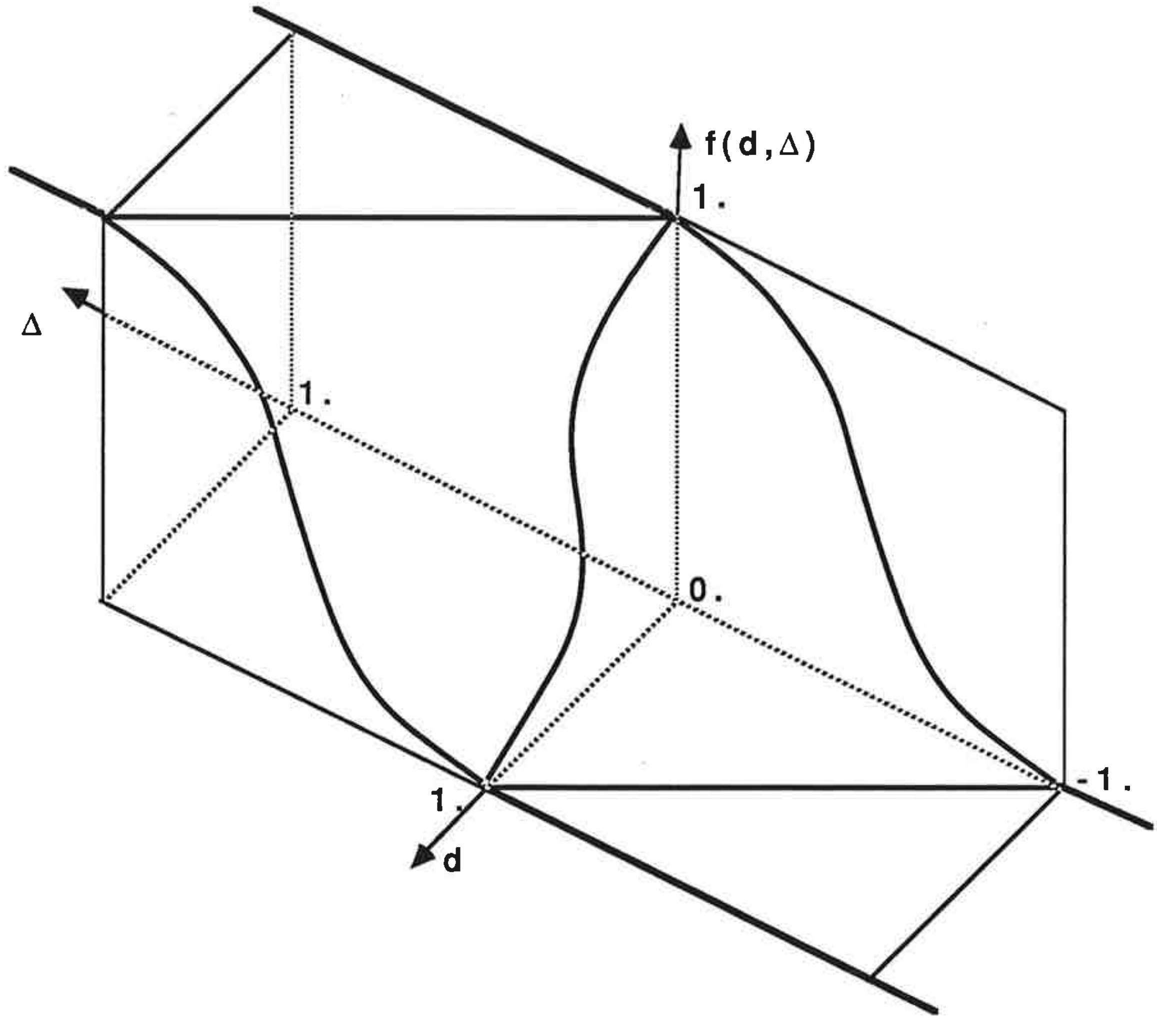

Fig 4 : Normalized transition function f(d,Δ)

3.3 Two examples

A first example with an inequality constraint is the one of any motion for which we want to warranty a floor support : we can define some open chains to correct and ask only for the altitude of some predefined points on these chains to be positive. Then the thickness of the transition zone determines the smoothness of the transition in switching from Direct to Inverse Kinematics as well as in the opposite direction. This symmetric mechanism can be avoided by mean of an automata detecting the transitions and deciding wether or not to apply the transition function ; this will be the scope of a walking application detailed in part 5.

Another example with some equality constraints is a complex arm motion which we want to correct to hold a glass of water nearby the horizontal . We need for this to specify an Equality constraint for the two angles attached to describe the rotation of a reference plane of the glass with respect to the world xy plane. Each constraint has its own transition function and the general form of the solution becomes vectorial as describes in the next chapter.

4 Vectorial Constraint Space General Solution

When multiple constraints are applied to a TRAINEE , each of them has its transition function and the general form of the solution becomes :

$$\Delta\theta = J^+(F.\Delta x + (I- F).J\Delta z) + (I-J^+J)\ \Delta z$$

where F is a diagonal matrix of the previous transition functions

As matrices multiplication is not commutative, even with diagonal matrices (of different diagonal values), this expression cannot be simplified as the scalar one which could be reduced to :

$$\Delta\theta = f.J^+\Delta x + (I - f.J^+J)\ \Delta z$$

which clearly shows the two extreme forms of the solution for f equal to 0. or to 1..

These forms still appears when the diagonal values are all 0. or all 1. . In the intermediate cases the behavior in the constraint space is the one expected and that there is of course a composition of the different solutions in the joint space.

We can illustrate this with a simple case of a two dimensional constraint space where the first transition function presents a 1. (strict Inverse Kinematics) and the second a 0. (strict Direct Kinematics). The solution is :

$$\Delta\theta = J^+ [\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} .\Delta x + \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} .J\Delta z\ ] + (I-J^+J)\ \Delta z$$

$$\Delta\theta = J^+ \begin{bmatrix} x_1 \\ j_{21}z_1 + j_{22}z_2 \end{bmatrix} + (I-J^+J)\ \Delta z$$

This second expression shows that the expected behavior will occur as seen in the first member of the solution . Now let us look at the final form of the solution in the joint space :

$$\Delta\theta = J^+ [\begin{bmatrix} x_1 \\ j_{21}z_1 + j_{22}z_2 \end{bmatrix} - J\Delta z\ ] + \Delta z$$

$$\Delta\theta = J^+ \begin{bmatrix} x_1 - (j_{11}z_1 + j_{12}z_2) \\ 0. \end{bmatrix} + \Delta z$$

The final solution gathers the different components due to the main and the secondary task ; as the main task still holds a strict inverse Kinematics component for x_1 its contribution appears here :

$$\Delta\theta = \begin{bmatrix} z_1 + j^+_{11}(x_1 - (j_{11}z_1 + j_{12}z_2)) \\ z_2 + j^+_{21}(x_1 - (j_{11}z_1 + j_{12}z_2)) \end{bmatrix}$$

5 Case-Study : walking

This example is motivated by a previous study we made on the extension of a kinematic walking model built from experimental data (Boulic and Thalmann 1990). In fact we had the intuition of the need of the Coach-trainee methodology from the problematic of correcting such motion.

This case study is limited to a scalar constraint space : the respect of the floor support for both legs while walking at arbitrary speed and personification. We use an inequality constraint of the form : foot_heigh >= floor_level with a transition zone .

As noted before , the proposed method cannot be directly applied to walking due to the discontinuous nature of the heel contact while the toe off phase is rather continuous.In fact if no transition zone is applied we may have the magnetic shoes effect obtained by most of the previous studies in walking simulation (Cremer 1989). But if we introduce a transition to deal smoothly with the toe_off phase then we will also have a smooth heel_strike phase which introduce a sort of walking on a mattress.

As our purpose here is to walk on a standard floor we have to distinguish two different states of a walking leg so as to apply to it the smooth switching or not. So each leg maintains a dissymmetrical switching automata which evaluates the next Kinematic method with respect to the current one and to the current transition function value :

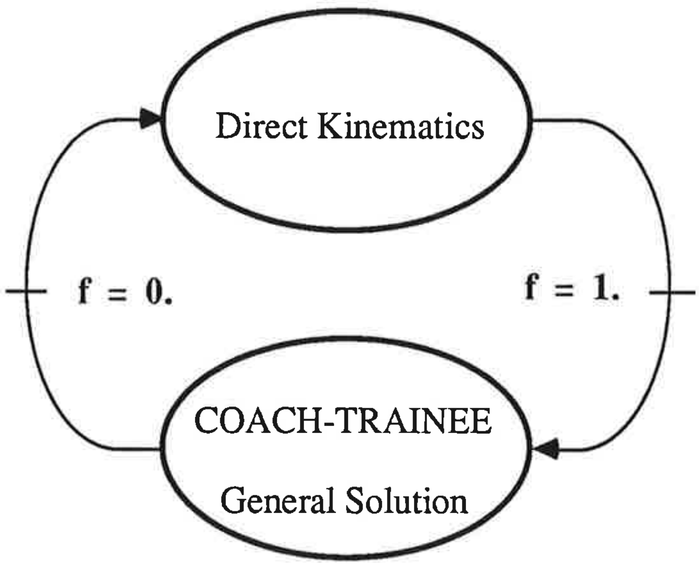

Fig 5 Dissymmetrical switching automata

Apart from this switching aspect this case introduces another important extension of the correction method due to the fact that we don't walk only a point submitted to the floor_level constraint but on an entire foot . An ideal solution would be to detect the most demanding vertex on a polyhedral approximation of the TRAINEE foot and to apply the correction method on this point while evaluating the transition function with the corresponding point on the CAOCH. This is too costly and we restrict this idea to four special points (Fig 6) :

- heel and foot_base linked to the ankle joint
- toe_base and toe_extremety linked to the toe joint

For each time step the COACH-TRAINEE general algorithm (symmetrical case) is then :

1 - Evaluate the height of the four special points and select the lowest one to drive the correction method ; this determines the current main Kinematic chain .

2 - Evaluate the TRAINEE deviation Δ (cf 3.1 or Fig 3) of this point as the first component (called the nominal task) of the main task .

3 - Evaluate the secondary task as the saturated COACH_TRAINEE gap (little movement hypothesis) plus the COACH Current Kinematics.

4 - Evaluate the transition function f and complete the main task with the weighted nominal and mapped secondary task.

5 - Verify the corrected result by re-evaluating f .

- if $f = 1.$ -> the constraint is not met , the time step is shorten and the algorithm begins again at stage 1

- if $f \neq 1.$ -> the strict constraint is met , the nominal task may not be met but we bypass this to favour the fulfillment of the Direct Kinematics which is our final goal. The result is validated and the time-step is lengthened.

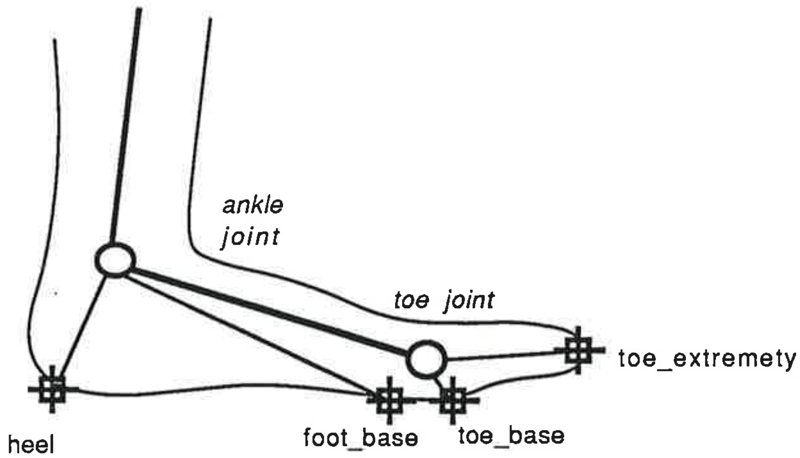

Fig 6 Points submitted to the floor level constraint

In this walking application we use two COACH-TRAINEE chains which are independently managed with their own automata and transition function. But as soon as one COACH-TRAINEE chain doesn't respect the constraint and must change the current time step the other one must also be re-evaluate with this new time-step.

This problem is rather penalizing but its the only way to have a global coherent configuration of the walking structure.

Another time related problem is the adjustment of the time step to provide exact frame time synchronization all along the process of correction if a video rate recording is required.

This method is currently under investigation and we think that walking is a good testbed application to evaluate its performances.

6 Conclusion

It is too early to make a quantitative evaluation of the performances of the correction method but we believe that it greatly extends the scope of predefined motions (rotoscopy , specialized model , key-framed etc..).

Moreover, a new methodology emerges for motion conception and edition which takes profits of the COACH-TRAINEE correction method. The following functional diagram is organized around a key module of motion composition (blending).

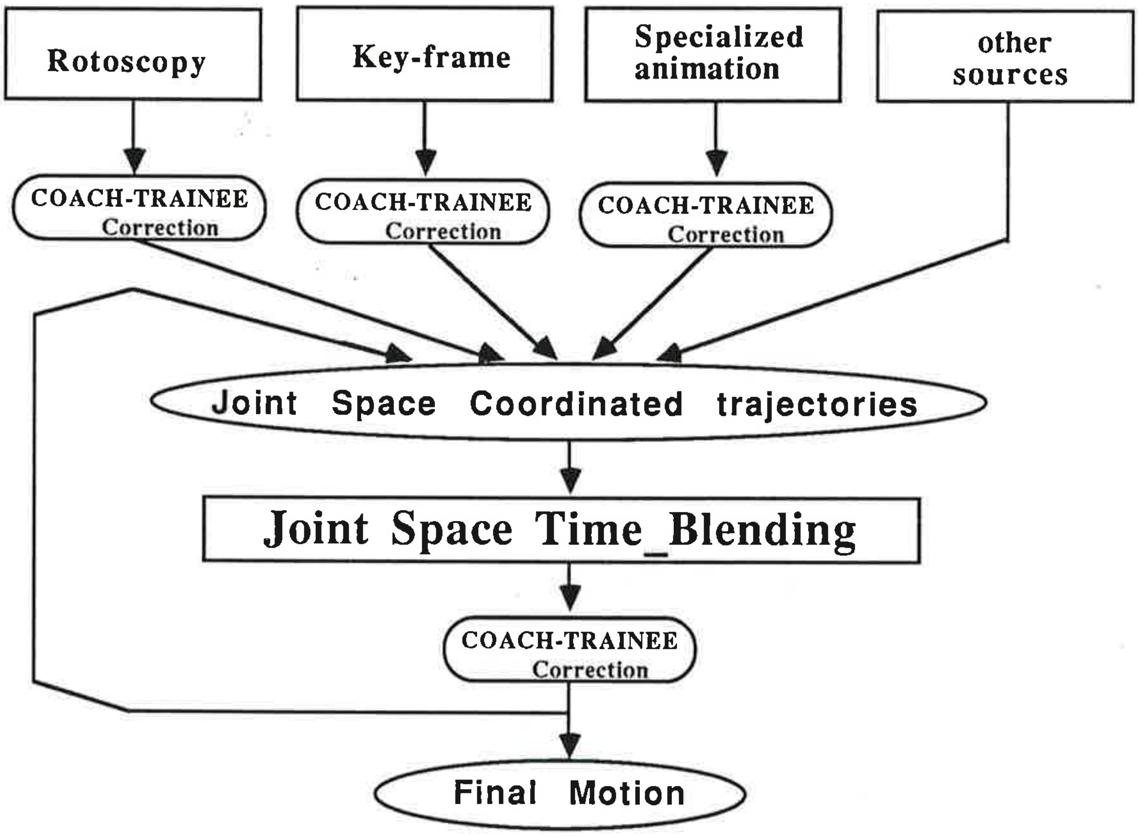

Fig 7 : Methodology of motion edition

Indeed, one of the critical phase in motion edition is the transition phase between motions of different sources and natures. If COACH-TRAINEE approach can be applied to them separately it can also help to the correction of these transition phases defined in the Blending module. As the resulting trajectories are of same nature as the incoming ones, the blending process can use them as any other sources.

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