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Morphological and stance interpolations in database for simulating bipedalism of virtual humans

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Abstract We present a computer tool for testing walk hypotheses for human beings. This tool aims to generate plausible walking movements according to anatomical knowledge. To this end, we introduce an interpolation method based, on one hand, on morphological data and, on the other hand, on stance hypotheses and on footprint hypotheses. We want to test these hypotheses for application to the reconstruction of early hominid walking. We interpolate from a specific representation of the movement—a characteristic relative displacement. First, we use a motion capture system to acquire real movements of a walk cycle, and we propose to represent them by using a generic parametric model. Thus, we create a database of movements. The interpolation process produces, thanks to this database, a retargeted motion adapted to the morphology of the considered targeted skeleton. The interpolation is done according to three main hypotheses. The first concerns the reference stance, the second the lateral spacing between the feet, and the third the length of the step. In the introduction, we refer

to related work. Then we propose the two following points of our method: the 3D representation of our motion representation and the multidimensional interpolation method applied to this representation. The interpolation method addresses morphological adaptation, and the use of an inverse kinematics solver addresses the computation of skeleton movements. The self-coherent validation process aims to test the coherence of the proposed method. The results propose an application to a virtual skeleton of Lucy (*Australopithecus afarensis* A.L. 288-1) reconstructed from real data. Finally, the relevance of the method for anthropological investigations and for animation purposes is discussed and future work is discussed with respect to the limitations of the proposed method.

Keywords Motion retargeting · Biomechanics · Bipedalism · Morphological and multidimensional interpolations · Virtual human ·

1 Introduction

Realism in retargeted motions is an important issue, given that ensuring foot contact with the ground is not enough

to ensure the realism. Fields of application are numerous: analysis of movement, biomechanics, animation and simulation in virtual environments, medical simulation, and anthropology. Here we present a computer tool for testing locomotor hypotheses and generating a plausible bipedal

walk for virtual humans according to anatomical knowledge. The tool integrates an interpolation method based on morphological data and both stance and footprint hypotheses. We focus on the simulation of locomotion [22], which may be divided into three main classes:

- Inverse kinematics (IK)
- Inverse dynamics
- Retargeting and motion capture

In the inverse kinematics technique, the joint angles are computed step by step, according to a skeleton articulation description and, sometimes, to biomechanical data. This computation can be done efficiently, but there is no guarantee of physical realism. Furthermore, the computation of the whole model may be too time consuming for use in practical calculations [2]. Boulic et al. [1] have proposed a complementary technique based on inverse kinetics that controls the center of gravity of any articulated figure in single support. Nevertheless, inverse kinematics is widely used to ensure foot contact with the ground [2] and to avoid sliding. Choi and Ko [5] proposed a similar real-time technique where the output vector is a composition of all positions to be preserved, among which are the positions of the hands and feet. B-spline hierarchies have also been used to interpolate the solutions calculated by an inverse kinematics solver [16]. Other works have studied more localized adaptations and focused on specific parts of the human body. Kovar et al. [15] proposed an analytical method to specify the constraint of the supporting foot, avoiding penetration in support or slip on support.

The inverse dynamics technique computes the correct forces and torques that are applied at the joints to execute a given motion. Thanks to the use of inertia data, this computation produces smooth results but may involve stances that are not humanly feasible [12]. For our purpose, we have an additional limitation because information about masses of fossilized hominids are not pertinent enough to perform such dynamic computations.

The retargeting motion techniques are based on deformations of captured movements or on interpolations between these movements. Witkin et al. [29] have described a direct editing of motion curves called “motion warping.” Bruderlin and Williams [4] have proposed a motion displacement mapping by using signal processing methods. Moreover, a simplified vision of the retargeting consists in reproducing movements of characters with different morphological proportions [9] while preserving important constraints like contact of the foot on the ground. When a constraint is lost during the modification, a solver of spacetime constraints calculates an adaptation in order to restore it. The skeleton model may be improved by the addition of forces related to the muscles [13] or by physics-based transformations [24]. Monzani et al. [20] proposed using an intermediate skeleton and mixing inverse kinematic and retargeting. This technique allows the

conversion of movements between actors with different hierarchical models and geometrical skeletons. Savenko and Clapworthy [26] studied a related problem. They proposed an algorithm that analyzes the movement, classifies it, determines its structure, and identifies the constraints. These constraints are then used in the adaptation. The decomposition of the movement in steps identifies the contact phases between the foot and the ground. This retargeting algorithm ensures that the movement is acceptable from a biomechanical point of view and corrects the possible artifacts. An interesting complementary approach was developed by Bregler et al. [3]. This approach identifies the kinematic chains from video sequences for the reconstruction of human or animal skeletons and analyzes tracker trajectories.

Large motion databases are now commonplace in applications that require realistic character animation. These databases are especially valuable because they can contain many variants of the same kind of motion. Kovar and Gleicher [14] provide automated methods for identifying similar motions in a data set and using them to build a continuous parameterized space of motions. Rose et al. [25] define the parameterized motions as verbs and the parameters that control them as adverbs. Verbs can be combined with other verbs using transitions between them, radial basis functions, and low-order polynomials. Another use of movement databases has been proposed thanks to learning models of human poses [11], which lead to different styles of IK.

The synthesis of bipedal walk uses many models and tools that are often complementary. In our approach, we directly modify the movement from our database of acquired movements. The issue is to know how to modify the movement, so that this new movement is acceptable or realistic for a given human. This implies having a representation of the movement, specifying a set of acceptable constraints, and defining a set of influential parameters. As reported in [9], the length of the members is very influential on the generated movement. In the same way, bone structure and articulation configuration [20] modify the inverse kinematics solution. We integrate these parameters in our interpolation method, and aspects of multisource interpolations and extrapolations are an essential characteristic of the techniques we use.

We propose a method for testing the influence of two sets of hypotheses on bipedal gait and for comparing the produced angular trajectories. The first set of hypotheses is natural, based on well-known parameters, and related to morphology and joint limits. For application to early hominids, the second set of hypotheses is necessary, based on uncertain data, and related to natural stance and footprints. We use a motion-capture and an interpolation-based retargeting approach to study the effect of these significant parameters on human walking. Moreover, to observe the rules of biomechanics, we use an inverse kinematics solver on the targeted skeleton. In the remainder of

this paper, we introduce the construction of our database and show how we represent our skeleton and its gait. Then we present our method for computing new movement using influential parameters and inverse kinematics. Finally, we propose a self-coherent validation step and discuss the first results on australopithecus data.

2 Problem statement

2.1 Real-movement data

The use of real-movement data induces the definition of a pretreatment method, which constructs a parameterized model of the acquired movements,¹ as shown in Fig. 1.

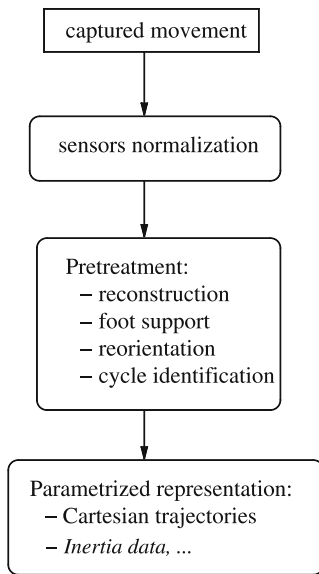


Fig. 1. Overview of pretreatment protocol

This method is based on part of the work of Ménardais et al.[18] for skeleton representation, for reconstruction of captured movement by guessing the possibly missing sensors, and for walking reorientation. To correctly deal with the captured movements, we have developed a normalization of sensor labels that allows acquisition with any sensor positioning and for any targeted skeleton. This ensures the correspondence between the anatomical landmarks, either on the skeleton or on the real human, and acquisitions with different sensor positionings due to different acquisition protocols. From these acquired trajectories a component extracts generic representations from the movement, such as relative landmark displacements. Some mechanical data, such as the inertia matrix, may also be extracted to introduce dynamic corrections. These generic representations are the inputs of the interpolation system. We

want to study separately the influence of morphology and locomotor parameters, like footprints or posture, on the articular trajectories. Thus, for the motion-capture part, we had to choose people with very different morphologies and ask them to walk with three different stances, as presented in Fig. 2. The first stance was a normal stance and corresponds to the character (human being) in a natural position at rest. Then we asked the subjects to walk as they thought a monkey would walk, producing a bent stance. The third stance was an intermediate stance between bent and erected, which could be like an australopithecus. This panel is defined for covering the three main hypotheses concerning plausible early hominid stances [10] [27]. For the same reason, we also asked the subjects to perform variations in the length of their steps and in the lateral spacing of their feet. In this way, we increased the diversity of our database and thus the possibility of studying the influences of the various parameters. All these gaits were integrated in our interpolation database, which contains data from 41 different subjects in the three defined stances.

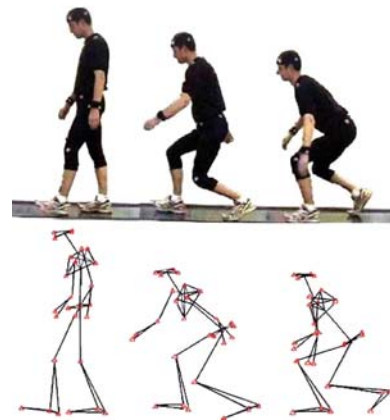


Fig. 2. Three walks with different stances and their 3D visualizations

2.2 The kinematic chain

We use a kinematic chain to represent the lower part of the virtual skeleton. This chain is similar to the one proposed in [23] and is composed of five rigid bodies, which model the limbs of the skeleton: one pelvis, two femurs, and two tibias. For the moment, due to missing data for our targeted skeleton (Lucy A.L. 288-1), we stop the model at the ankles and do not use a foot model. This limitation will be addressed in future work with the correct reconstruction assumptions. The root of this kinematic chain is the center of the pelvis, which can rotate about its three main axes and is modeled by a ball and socket joint with 3 rotating degrees of freedom (DOFs). Sagittal and lateral

¹ Motion Capture system: Vicon 370, Oxford Metrics

translations are ignored because we are working with relative displacements. But these translations are taken into account when using the walk model in a global virtual world [19]. Vertical translations are assumed by the alternative contact of the effectors on the ground. Each hip is linked to the pelvis by another ball-and-socket joint. Each knee is represented by a pin joint with 1 rotating DOF, which is sufficient for the target application of global motion. We thus obtain 11 DOFs for the kinematic chain presented in Fig. 3. Interpolations and inverse kinematics are performed on this structure, whereas the upper-body animation is, for the moment, that of a simple walking movement.

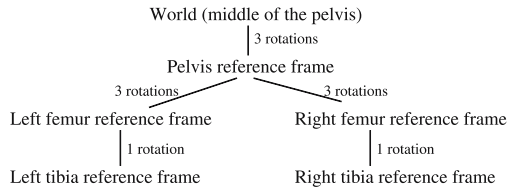


Fig. 3. Structure of kinematic chain

2.3 The *poulaine*: a characteristic representation of the gait

Since we want to use an inverse kinematics solver to generate the walking movement, we have to define the lower-body effectors. In general, these effectors are the feet. In our case, because of missing data about the feet of the considered early hominid (Lucy), we have chosen the ankles as lower-body effectors. In this work, the so-called *poulaine* is defined as the Cartesian displacements of the ankle as seen in the coordinate frame of the center of the pelvis (root). This *poulaine* is well suited to describe a walk cycle [21, 28]. By changing values, it is possible to modify the *poulaine* and thus to adapt the gait to the target skeleton and to external constraints by preserving the *poulaine* characteristics. Calculating the articular trajectories with respect to this modified *poulaine* means solving an inverse kinematics problem presented below.

3 How to proceed

Our framework is organized as follows (Fig. 4). A database D of *poulaines* is built according to captured motions and normalized by the length of the members. First the user, the animator or the anthropologist, specifies the anatomical description of the skeleton to be animated. According to these new data, a scale is performed on all the database trajectories contained in D . Second, the user specifies the footprints and the rest posture that are required for

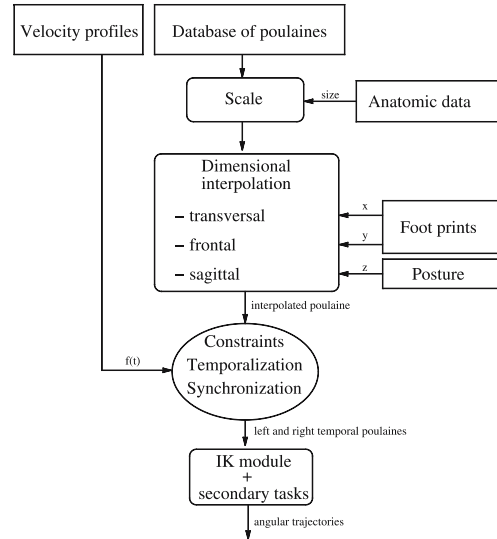


Fig. 4. Overview of retargeting algorithm by interpolation method

the new character. The interpolation module selects data from D that best correspond to those requirements. We dissociate our technique of interpolation along the axes of the anatomical plans. Then, if necessary, we perform a space constraint check on the resulting *poulaine*. With the velocity profiles $f(t)$ we are able to compute a temporal retargeted *poulaine*. After that, we calculate the other side's *poulaine* and synchronize them. Finally, these *poulaines* are used as inputs of an inverse kinematics solver. The resulting angular trajectories are then sent to visualization.

3.1 Morphological and postural data

We have acquired the gaits of 41 subjects for normal, intermediate, and bent stances. These subjects are chosen with as different morphologies as possible. From this database we extract the lengths of the members of the subjects. The lengths and associated ratios for five of the subjects are presented in Table 1: two women (165 cm and 170 cm), one 2-year-old child (78 cm), and two men (165 cm and 190 cm). These subjects characterize the di-

Table 1. Lengths of members of five subjects

Subject	Woman 1	Woman 2	Child	Man 1	Man 2
Femur (cm)	45.2	46.9	20.3	41.9	50.6
Tibia (cm)	40.4	39.7	18.3	43.7	46.6
Femur/tibia Ratio	1.12	1.18	1.11	0.96	1.09
Leg (cm)	85.59	86.6	38.6	85.6	97.2

versity of the database both in morphology and in proportions.

Typical values of articulation angles for the three main stances are:

1. Normal: $10^\circ \pm 2^\circ$ for hip and $-22^\circ \pm 3^\circ$ for knee
2. Intermediate: $28^\circ \pm 4^\circ$ for hip and $-50^\circ \pm 5^\circ$ for knee
3. Bent: $37^\circ \pm 4^\circ$ for hip and $-80^\circ \pm 7^\circ$ for knee

The angle of the hip is measured between the vertical axis and the femur, and the angle of the knee is measured between the prolongation of the femur and the tibia, as shown in Fig. 5. These angles are measured when the sagittal projection of the ankle of the subject is under the center of the pelvis during the phase of support. This corresponds to the reference stance.

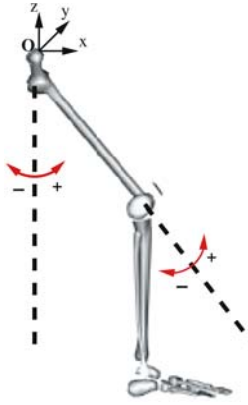


Fig. 5. Definition of reference frame and orientation of angles

3.2 Poulaine modeling

The following reference frame, shown in Fig. 5, is used to represent the motion:

- The center of the reference frame O is the center of gravity of the human (middle of pelvis, root of skeleton).
- The x axis represents the direction of displacement of the reference frame (orthogonal to frontal plane), and thus the x -coordinate governs the length of step.
- The z axis represents the vertical movement of the reference frame (orthogonal to transverse plane), and thus the z -coordinate governs the posture.
- The y axis is the vector defined (x, y, z) like that of an orthonormal right-handed frame (it is orthogonal to the sagittal plane). The lateral movement is represented on this axis, and thus the y -coordinate governs the foot spacing.

Although poulaines of very bent walks are often varied, the characteristics of their shapes are taken into account and we use a generic interpolation model, based

on four characteristic points, to represent them. These points are associated to four precise moments of the cycle. The mathematical representation of a poulaine must be parameterized by their coordinates and must also be at least cubic for the continuity between the four curves. So we choose to represent the trajectories by four cubic parameterized Coons curves [6], but any kind of generic representation respecting these constraints could be used. Each of the four curves $C_{i=\{1,\dots,4\}}$ are defined by two of the four characteristic points and tangents: $P_{j=\{1,\dots,4\}} = \{c_{x_j}, c_{y_j}, c_{z_j}, t_{x_j}, t_{y_j}, t_{z_j}\}$ such as $C_i = \{P_a, P_b\}, a, b \in \{1, \dots, 4\}$. These characteristic points are shown in Fig. 6:

- Point 1 represents the moment when the ankle reaches its maximum altitude. On the curve, this point has the greatest z component.
- Point 2 represents the maximum extension of the leg. On the curve, this point has the greatest x component.
- Point 3 represents the moment where the ankle passes on the vertical of the root of the support phase (natural stance). On the curve, this point is the point with the x -coordinate closest to 0.
- Point 4 represents the time of the maximum inflection of the leg. On the curve, this point has the smallest x component.

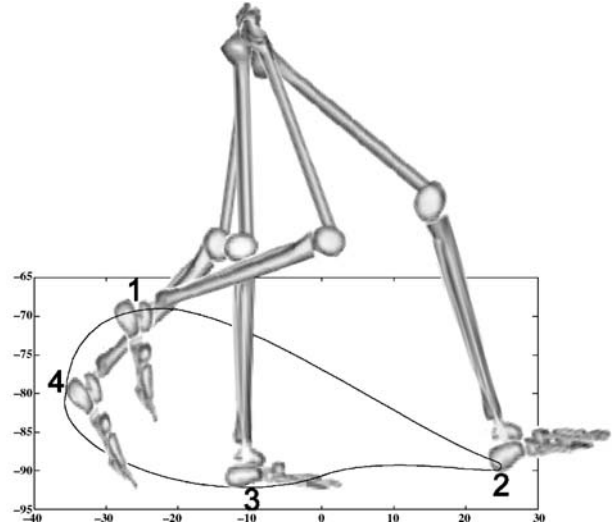


Fig. 6. Positions of four characteristic points within cycle

The associated tangents are computed automatically by an iterative algorithm that searches for the tangents that minimize the distance between the real and the calculated curve. After defining the intervals of seek $I = [first, last]$ of each tangent t_j and a threshold ε from which we suppose that distance between two points is acceptable, we

iterate on the tangents, create the corresponding curve N_i , and verify the distance until $|C_i - N_i| < \varepsilon$.

Our interpolation is made on the coordinates and the tangents of the four characteristic points. The shape of this curve does not provide us with the speed of the ankle. To control this speed, we use an average speed profile (ASP). The first stage of its creation consists in isolating the walk cycles and synchronizing them at point 1, where the speed is highest to avoid confusion. The second stage consists in calculating the speed profile for each motion in our database, $SP_{i=\{1, \dots, 123\}}$, using the motion capture files and the frequency of the recording. In the third stage, we normalize the SP curves to compare them:

- No two people have the same time duration of step t_{step} , so the curves are normalized according to this value ($SP = SP/t_{step}$).
- As no two people have the same leg length either, the feet do not travel the same distance d_{step} . We normalize the speed curves according to this distance ($SP = SP/d_{step}$).

We represent the average speed curve (ASP) by a polynomial function. Figure 7 shows this average profile and the polynomial interpolation (order 20) that characterizes it. It enables us to represent the curve with an average error lower than 1.36%. For each simulation step, this profile gives us, by integration, the position on the “ $S(t)$ ” curve (curvilinear x -coordinate). We then determine the value of the corresponding parameter on the cubic curve. This parameter allows us to compute frame by frame the position of the effectors on the trajectory.

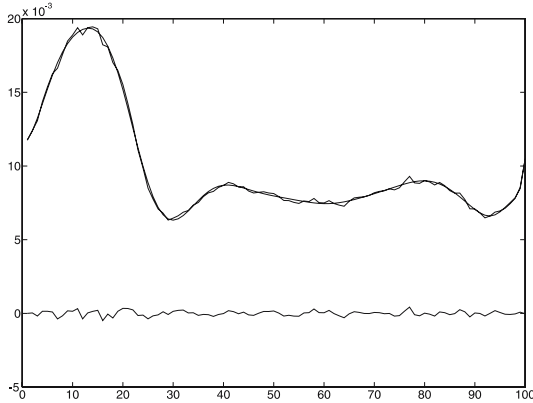


Fig. 7. Profile of average speed (ASP), its polynomial interpolation, and the difference between them

3.3 A multidimensional method

The main idea of our method is to separate the x , y , and z interpolations, which is why we captured the walks according to the most influential parameters on each axis.

These parameters, reflecting our choice of poulaine modeling (Sect. 3.2), are as follows:

- The rest stance of the human is associated to the z -axis. We characterize this parameter by the distance between the center of the pelvis and the ankle along this axis.
- The spacing of the feet during the support phase is associated to the y -axis. This parameter is the double of the distance between the ankle and the walking displacement axis.
- The length of the step is associated to the x -axis. This parameter is the length of the effector trace on this axis during a cycle.

We perform a morphological scaling of all the curves using the lengths of the legs. This scaling guarantees the adaptation of the acquired movements to the target skeleton, as proposed in previous works [9, 26].

Since the length of step characterizes the x motion, we select, in our set of normalized walks, the curve with the closest step length. The x components of coordinates and tangents of the characteristic points are stored.

Since the shifting of the foot spacing during the support phase characterizes the y motion, we select the curve with the closest foot spacing. The y components of coordinates and tangents of the characteristic points are stored. Using these two interpolations, we ensure the passage of the feet through prints on the ground.

For balance reasons [28], the rest stance characterizes the z motion. We thus select the walk with the closest rest stance. The z components of the coordinates and of the tangents of the characteristic points are stored.

As the chosen points are only the closest approximations in our database, it is necessary to perform corrections on the obtained poulaine. These corrections consist in performing an exact fitting of the step length, of the foot spacing, and of the stance. Furthermore, these corrections ensure that the ankle can follow the reconstructed curve by a space constraint solver.

3.4 Inverse kinematics solver

The calculated poulaine results from our retargeting, multidimensional interpolations, and speed control approaches. This poulaine constitutes the trajectory of the effector X . This trajectory is imposed in the classical inverse kinematics equation, based on the pseudoinverse of the Jacobian method:

$$\Delta\theta = J^+(\theta)\Delta X + \alpha(I - J^+J)\delta, \quad (1)$$

where J^+ is the pseudoinverse of the Jacobian J , θ the set of angles applied to the DOF, X the position vector of the effector, α a weight associated to the secondary task, I the diagonal unity matrix, and δ the parameter to optimize.

ΔX is given by the poulaine. The primary task consists in following the curve. The solution has a minimal norm, but in order to ensure that it observes joint limits and produces realistic trajectories, several secondary tasks must be proposed. To solve this inverse kinematics problem and control the movement by biomechanical knowledge, Nicolas et al. [23] proposed a solver where the primary task is to follow the poulaine, and secondary tasks ensure the observation of joint limits, the minimization of the rotational kinetic energy, and the observation of the stance of reference.

3.5 Method of self-coherent validation

The method that we propose for the validation step is a self-coherent validation process. We compare the initial poulaine of a gait with the produced poulaine according to data extracted from this gait. This comparison is done in terms of shape and speed and is performed for each initial subject. For each gait resulting from the database, the morphological and stance parameters, as presented in Table 1, are extracted from each skeleton model and each motion. Let us focus, for example, on the third subject in an intermediate stance and use it as the target skeleton in the proposed method. In Fig. 8, we compare the reconstructed poulaine to the acquired motion representing this gait. This comparison shows very few differences except the slight shift in shape, which is due to generic representation by a parameterized cubic curve.

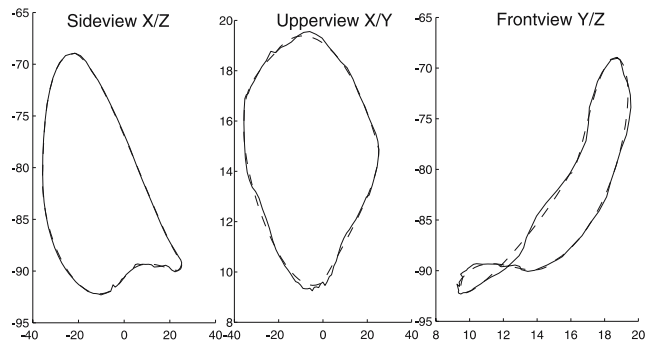


Fig. 8. Initial (solid line) and reconstructed (dashed line) poulaine in (x,z) , (x,y) , and (y,z) planes. Units in centimeters

The measure of the difference between the initial poulaine and reconstructed ones is evaluated by the root mean square (RMS) error:

$$e_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N (Initial(t_i) - Reconstructed(t_i))^2}, \quad (2)$$

where t_i denotes the discrete time and N the number of frames. We compute this error for each axis (x, y, z) and

then calculate an average value. For our example the RMS values are:

	x -axis	y -axis	z -axis	Mean value
e_{RMS} (cm)	3.65	0.70	1.48	1.94

This validation is performed for all acquired movements; the mean values and standard deviation (SD) for the whole database are:

	x -axis	y -axis	z -axis	Mean value
e_{RMS} (cm)	2.74	1.22	1.24	1.73
S.D. (cm)	1.18	1.12	0.76	0.82

Note that the mean error is under 3 cm and that the dispersion is low.

4 Results

The multidimensional method based on morphological and stance hypothesis data finds an application in the field of anthropology: it contributes to the drawing of a plausible walk for early hominids using anatomical and osteological data. Lucy (A.L. 288-1) is a very well-preserved specimen of the *Australopithecus afarensis* species, an early hominid that lived almost 3.3 million years old. The pelvic girdle and lower limb skeleton (pelvis, femur, and tibia) were reconstructed virtually and articulated in the UPR 2147 (CNRS) using casts of the fossil and following the principles described by Marchal and Berillon [17] and shown in Fig. 9.

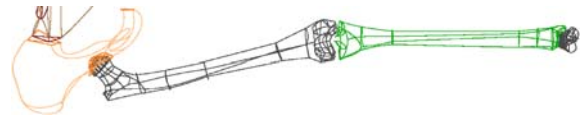


Fig. 9. Half of 3D model of Lucy's pelvic girdle and lower limb bones (right side in frontal view)

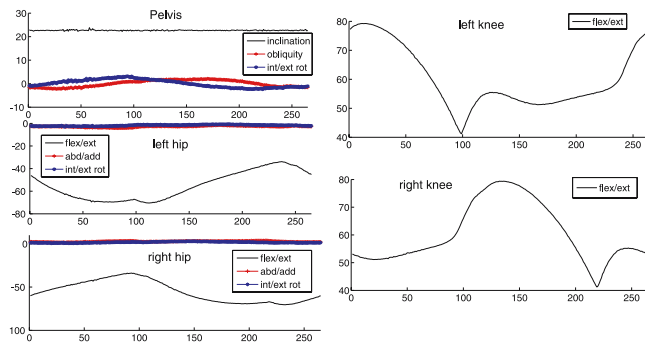
This reconstruction leads to the morphological and osteological data presented in Table 2. The values of the morphological parameters are relatively certain data, but the length of step, feet spacing [8], and the normal posture are hypotheses [7]. Using our multidimensional interpolation method, the three interpolated poulaines are:

- Length of step: a man shorter than average walking with a normal posture.
- Foot spacing: a man of average size with an intermediate posture.
- Posture: a woman of average size walking with a bent posture.

Table 2. Parameters for Lucy under anthropological reconstruction assumptions

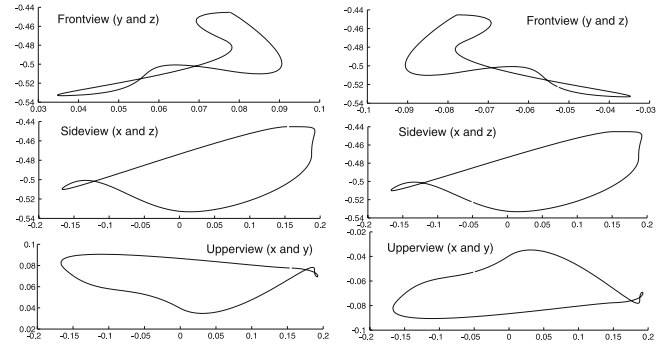
Subject	Lucy (A.L. 288-1)
Femur (cm)	26.50
Tibia (cm)	27.29
Step (cm)	35.0
Posture: hip/knee	17.14° / -31.62°
Feet spacing (cm)	4.0

Different subjects and different postures are selected for each poulaine. This diversity justifies our protocol of acquisitions of multiple subjects in multiple stances. Lucy's posture is widely discussed in the paleoanthropological literature [27]. Three current hypotheses exist: an upright, a "bent-hip, bent-knee," or an intermediate posture. The calculated trajectory thus combines three different curves and corresponds geometrically to an intermediate posture, between an upright human and a "bent-hip, bent-knee" human. Figure 10 shows angular trajectories obtained for the pelvis (3 DOFs), hips (3 DOFs), and knees (1 DOF). Note that the inclination of the pelvis is constant compared to the reference posture. As in normal human walking, the most important DOFs are the flexion/extension of the hips and the knees. Figure 11 shows the computed poulaine in the (y, z) , (x, z) , and (x, y) planes. These values are compatible with previous paleoanthropological studies on bipedal locomotion [10, 28].

**Fig. 10.** Angular trajectories of pelvis, hips, and knees for Lucy's skeleton

5 Conclusion

This work is applicable in such fields as biomechanics or anthropology. It makes it possible to test several locomotor hypotheses, such as anthropometric data, joint limits, length and spacing of steps, and posture of reference. In anthropology, given the nature of the fossil material, some of the parameters useful for construction of a complete

**Fig. 11.** Curves obtained for Lucy. Left and right poulaines in (y, z) , (x, z) , and (x, y) planes

model of the bipedal displacement of fossil skeletons are not known. The parameters used in this study then become hypotheses for anthropologists.

Our tool can also be useful for computer animators. Indeed, some parameters are sufficient for generating a plausible walk. The morphological values and the rest posture are in general known by animators because they seek to animate a known creature. And footprints are always necessary to produce a specific gait. Thus our technique takes these user parameters into account and can be applied to any bipedal character to return a biomechanically plausible walk. Moreover, we focus on straight-line locomotion. We do not introduce in our approach, by blending or motion editing techniques, adaptation to the environment or the generation of a turning walk. The aim of this work is to compute a plausible walk given morphological data and biomechanical rules. Thus, to evaluate our interpolation results and to remain close to the initial realism, we must compare the retargeted motion with real trajectories without any additional modification. Nevertheless, environmental adaptation and turning walk generation techniques [18] may be applied as postprocessing on our retargeted motion. In biomechanics it is thus possible to evaluate independently the influence of these factors on a bipedal movement of locomotion. The work also offers interesting prospects for medical applications. It would be possible, for example, to evaluate the influence of a rehabilitation procedure on a physically challenged subject.

In this work, we use geometrical and multidimensional interpolations. Within our application framework, we are aware that the physiological differences between real humans and an australopithecus are significant enough to be taken into account. Unfortunately, data of this type are not available given only Lucy's bones. We are working on improving our approach with dynamic interpolations according to anthropometrical tables. Separating the interpolation using the three axes of the anatomical plans can seem arbitrary, but the selected parameter for each axis seems obviously the most influential. Nevertheless,

we plan to use a more precise but more complex parameterization.

We have underlined the lack of a foot model due to the lack of data for our target skeleton. When the reconstruction assumption is available, we plan to add a link representing the foot and the associated joint representing the ankle. Perhaps it would be interesting to focus on a speed representation for each motion and for the associated interpolation method. We plan to continue increasing the size and diversity of our database of walks. To address

the whole area of bipedal walk, it seems that data about apes would be useful. We also plan to manage a parameterized speed profile according to the locomotion speed of the subject and the moment in the cycle. From the biomechanical and anthropological points of view, additional degrees of freedom such as a more complex knee articulation system would allow better realism and better interspecies generics. Thanks to the parameterized representation component, we can work on other types of representation of movement like biomechanical rules and dynamic calculations. These representations will allow the creation of an inertia database, in particular on upper-body motion.

² ATIP: Action Thématique et Incitative sur Programme

³ UPR 2147, CNRS, Dynamique de l'Évolution Humaine: Individus, Populations, Espèces (Paris)

⁴ UMR 5809, Laboratoire d'Anthropologie des Populations du Passé (Bordeaux)

⁵ Laboratoire de Physiologie et de Biomécanique de l'Exercice Musculaire (Rennes)

⁶ UMR 6074, Institut de Recherche en Informatique et Systèmes Aléatoires, Projet SIAMES (Rennes)

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