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Dynamics-based analysis and synthesis of human locomotion

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Abstract One of the best ways to synthesize realistic human motions is to animate characters from captured motion data that inherently respect motion laws. Retargeting and interpolation methods are often used to adapt these motions to different representations of the character and to various environmental constraints but they may introduce physical inaccuracies, although the synthesized motions are natural looking. This paper presents a method for evaluating the physical correctness of retargeted and interpolated locomotions using an inverse dynamics analysis. Furthermore, we propose to improve an initial database with analysed motions that are synthesized again by using a forward dynamics approach.
The analysis algorithm consists in determining the resulting forces and torques at joints. With this intention, we develop an automatic creation process of the mass/inertia model of the character. Then using support phase recognition, we compute resulting forces and torques by an inverse dynamics method. The retargeting and the interpolation methods change the physics of the motions. This change is evaluated by using the results of our analysis on artificial and real motions and by using literature results and experimental data from force plates. The evaluation relies on the study of several retargeting and interpolation parameters such as the global size of the character or the structure of the model. The output of this evaluation, the resulting forces and torques at joints, are used to produce physically valid motions by using forward dynamics simulation. With this purpose, we introduce forces and torques normalizations, and finally the synthesized motions may improve the initial database.

Keywords Motion analysis and synthesis · Kinematical influences · Physical realism · Virtual human

1 Introduction

Synthesizing realistic character motions remains one of the great challenges in computer graphics. It seems that obeying physical laws is an important criterion of plausibility of motion, and we think that it is why the dynamics of human gait have been studied for quite some time for animation purposes [7, 15]. The first method to produce such physically motions is to animate characters from captured motion data that are inherently valid. These motions are adapted to different representations of the character, to various environments or to additional kinematical constraints. The kinematic and kinetic adaptations (by interpolation, edition, retargeting or blending) may introduce physical inaccuracies in virtual human animation. It is thus necessary to be careful when such methods are used. Whenever the modifications introduce visually apparent errors in the physics of a motion, dynamics improvements may be added as a post-process or may correct the adaptation algorithm. To this end, Safonova and Hodgins [13] have proposed a method for analyzing the correctness of some physical properties in linear interpolated motions.

In this paper, we present a dynamics-based validation for retargeted and interpolated motions to improve an initial motion database thanks to a dynamics-based synthesis. We study the dynamical correctness of the algorithms through the change in the physics of the adapted motions. This validation relies on the creation of a biomechanical skeleton, i.e. a skeleton including information of masses and inertias, and the computation of the resulting forces and torques. Analyzing dynamics requires a high number of parameters constraining the motion (including ground support phases) and concerning the subject (including masses and inertias). Our goal is thus to propose a method to analyse, validate and synthesize locomotions of virtual human characters. This method can be expressed by three consecutive subparts:

- The description of an automatic, generic and stand-alone computation process of the dynamics of a locomotion including the evaluation of the parameters of the motion and the subject
- The application of this process for validating a motion adaptation algorithm with the separation of the influence of retargeting and interpolation
- The adaptation of the obtained forces and torques at joints in order to synthesize new motions improving the initial database

The remainder of this paper is structured as follows: Sect. 2 reviews the related works and our contributions, followed by an overview of our system in Sect. 3. The process used for the creation of the biomechanical model of the character is outlined in Sect. 4. Issues concerning dynamics-based analysis are developed in Sect. 5 and experimental results are presented in Sect. 6. Finally, we present our forward dynamics-based approach in Sect. 7. In Sect. 8, we summarise our contributions, discuss the validation approach and outline possible future research directions.

2 Related work and contributions

The approach of using both motion analysis and synthesis allows for a coherence in the animation of virtual human motions. The analysis extracts the data (such as trajectories) and invariants (such as laws) of the motion. These parameters can then be used to synthesize natural looking and physically valid motions. To simulate this interaction, two complementary approaches have been proposed: the first introduces physical simulation during the motion synthesis and the second corrects the motion after the synthesis, thanks to its analysis.

The first approach has been explored the most, starting with the joint use of space-time constraints on positions and forces [10]. But the optimisation of the forces at the joints involves long computing times. To reduce this complexity, constraints on torques have been added that include the mechanical constraints and the motion style [1]. The zero moment point (ZMP) can then be used to maintain the balance [14, 19]. The method has been extended to avoid the iterative process searching for optimal solutions at each frame. This method is called dynamics filtering [17]. The authors use a double filtering of the parameters to verify dynamical constraints. The first filtering predicts the next vector state according to kinematical and dynamical constraints such as the behaviour of the ZMP and the initial posture or the limitation of angular moments. The second filtering corrects the residual inconsistencies between the positions, velocities and accelerations. Another possibility consists in extending the pose control graph of generating models with given postures from motion captures. This method can be used to take into account local contacts and collisions [3, 19]. In these approaches, angular moments are added to those computed by the controllers. These moments can be computed, for example, as impulses to return to the initial motion by using a motion graph [3] or blending [20] methods.

The second approach is more recent, only a few works have studied the physics in interpolated movements. From the idea of determining the kinematical naturalness of a motion, some researchers study the dynamical naturalness. Safonova and Hodgins [13] propose an analysis of the conservation of basic physical properties in interpolated motions such as linear and angular momentum, static balance or friction on the ground. They suggest small modifications to the standard interpolation technique that in some circumstances produce significantly natural looking motions. In their approach Ko and Badler [9] show it is possible for part of the motion control, based on inverse dynamics, to influence the locomotion synthesis. This control manages the balance of the character and preserves the forces at the articulations within empirical intervals of data from literature.

In this work, we propose an approach of interaction based on the dynamics analysis and synthesis of locomotion adapted from a motion database. We first present a generic approach for validating a method of motion adaptation through the change in the forces and torques at joints. We pay special attention to the resulting ground reaction forces, because we can compare them with experimental data from force plates. Our approach relies on the representation of the character including mass and inertia information needed to solve the fundamental laws of physics. Our validation algorithm relies on the study of several retargeting and interpolation parameters such as the global scale of the character, the structure of the skeleton and the length of step. Then, we present a dynamics-based synthesis approach using normalized physical data.

The dynamics-based analysis and synthesis are independent of the method used for the motion adaptation. Thus our contributions can be summarised as follows: the evaluation, for validation purposes, of the resulting forces and torques applied at the joints of an automatically created biomechanical skeleton, and the synthesis of physically valid locomotion using the results of this evaluation.

3 Overview of our system

The overview of the process is presented in Fig. 1. In this process, the motion database is built with captured locomotion. In [12], we presented the retargeting algorithm and the motion interpolation approach. They are based on normalized representations of the character and the locomotion. These kinematical adaptations may introduce physical inaccuracies in such synthesized motions. An inverse dynamics-based analysis provides then information on the physical correctness of the motion and also the resulting forces and torques at the joints. In [11], we proposed validation steps of this analysis. Finally, a motion synthesis, using these forces and torques and a forward dynamics-based algorithm, is used to improve the initial database.

Some questions can then be raised:

- Are the adapted motions physically valid?
- If so, what are the limits of the method?
- Are these limits due to the retargeting or to the interpolation?
- How can we add new motions to the initial database by using the results of the previous step?

In this paper, we try to answer these questions and illustrate them in our adaptation method, but the proposed approach is generic and suitable for any method (interpolation, edition, retargeting or blending).

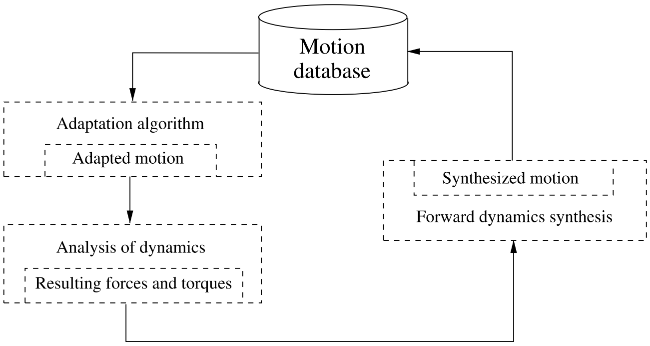

Fig. 1. Our system overview with kinematical adaptation, dynamics-based analysis and synthesis using and improving a motion database

To solve the fundamental laws of physics, and thus to analyse the dynamics, we need to evaluate the parameters concerning the character (see Sect. 4). We start by defining the hierarchical description of the skeleton, i.e. the mechanical model defined by the positions of the articular centres linking the limbs. We further add all the needed information such as masses, lengths, circumferences and inertias of the limbs, to the model by using anthropometrical tables [6] and regression laws [16].

The second fundamental part is to evaluate the parameters constraining the motion, i.e. the external forces acting on the body (see Sect. 5). To solve this problem, the angular accelerations at joints are needed. The first step is to convert the input 3D motion into a joint-angle motion. Then, using support phase recognition, we compute the resulting forces and torques by an inverse dynamics-based algorithm.

To synthesize new sets of physically valid motions, we normalize the extracted forces and torques by the global mass of the character (see Sect. 7), which is the most influential parameter that has been identified by our studies on the influences of the retargeting and the interpolations on the dynamics (see Sects. 6.2 and 6.3).

4 Creation of the biomechanical model of the character

In this section, we present the process used to create the biomechanical model of the character. We start by defining the mechanical model describing the hierarchy and the degrees of freedom of the skeleton (in Sect. 4.1). Then, we automatically upgrade the skeleton with the mass and inertia of each limb (in Sect. 4.2).

4.1 Mechanical model of the articulated skeleton

We compute an articular model for two reasons: to map the acquired motion on an angular-based skeleton and to use the anthropometrical tables describing physical properties from distances between articular centres. At each frame, we compute the three-dimensional positions $P(a)$ for each articular system a that we want to simulate. We use the set of three-dimensional positions of the landmarks $P(l)$. We just have to associate at least one $P(l)$ with one $P(a)$. The main interest is that it helps us to define a very accurate position of an articular centre or a virtual position like the root of the skeleton (using pelvis landmarks, for example). Moreover, it allows us to define articular centres and then to define an articular model from any marker set.

Each articular centre is described thanks to the modified notation of the Denavit–Hartenberg representation [8]. This representation is a systematic approach to assigning and labelling an orthonormal $(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ coordinate system to each robot joint. It is then possible to relate one joint to the next and ultimately to assemble a complete representation of a robot's geometry. Four parameters are used to define a linear transformation matrix between two successive coordinate systems associated with each joint. These parameters are the length of the link d_j, the distance a_j, the rotation α_j and the angle θ_j between the joints. The modified representation is adapted within the framework of the representation of a virtual human skeleton. Indeed, the hierarchy of our skeleton is directly incorporated in the representation, as well as the expression of the position and the orientation of a joint in the parent joint reference frame. Our system computes, for the whole motion, average values of distances between the articulations. These values define the translation parameters d_j and a_j. We just have to provide the rotational parameters α_j and θ_j.

4.2 Attaching mass and inertia

The mass and inertia of each limb provides the necessary physical information, which enables us to solve the problem of inverse dynamics. Since anthropometrical tables are different depending on the gender of the character, this information is provided by the user. For the same reason, we have to assign semantics to the skeleton, i.e. associate a segment between two articulation systems to a human limb. The semantics can be given manually or assigned automatically if the articular systems have preset labels.

We model limbs by using cylinders of homogeneous density because most of the anthropometrical tables and laws use this representation. From the evaluation of the lengths of the limbs (a_j parameters), we are able to estimate the total human height and mass by using tables described in [6]. Then, we use linear regression laws [16] to estimate masses and inertias for each limb.

5 Evaluation of the external forces acting on the body

Because solving dynamics needs angular acceleration data, we have to compute the articular trajectories (in Sect. 5.1). For that, we geometrically reconstruct the postures according to the motion and the biomechanical model thanks to the projection of this motion to the model. Then, we compute resulting forces and torques (in Sect. 5.2).

5.1 Articular trajectories

In this section, we address the mapping issue computing the joint-angle posture of the character from the 3D positions of the articular centres. In general, mapping a motion to a physical model is an under-constrained problem and optimisation requires additional metrics to find a unique posture, for example with optimised-based IK approaches [18] or spatial constraints [5] to preserve end effector positions.

We solve the mapping problem for each articular system (i.e. co-localised Denavit–Hartenberg joints set) in sequence by using direct geometrical reconstruction, i.e. computing the rotation matrix between the current and the next articular centre, allowing it to be as close as possible to the desired position.

- If the articulation is a pin joint, the dot product between the normalized vectors representing the limbs gives the *cosine* of the required angle θ'_j. We add θ'_j to its initial value defined by the mechanical model.
- If the articulation is a spherical joint, we must choose the rotation matrix among an infinity of solutions. But we often have additional constraints, which reduce the number of solutions. For example if the next articulation is a pin joint, we can determine the future error and then choose the rotation matrix minimising it. Average values can also be computed as long as the next articulations are pin joints for minimising the successive errors. If we do not have additional constraints, we compute the minimal rotation relative to the previous reference frame.

5.2 Resulting forces and torques

In this section, we present the application of Newton's second law of motion, which is the core of force and torque computation in the inverse dynamics process. Thanks to the knowledge of the ground support phases and the biomechanical model of the skeleton, we are able to compute the resulting forces and torques acting at the joints of our model. The structure of Newton's second law of motion depends on the external forces applied to the body. We solve it according to the external forces, which are the ground reaction forces. For locomotion, there are three different states: single support, double support and no support. For this support recognition, we use the method that we have extensively described in [11].

Newton's second law has two parts that are presented separately for each of the three cases of support states.

Linear form of Newton's second law:

The summation of external forces acting on a limb l is equal to the product of its mass m_l (supposed constant) by the acceleration $\boldsymbol{a}$ of its centre of gravity G_l:

$$\sum \boldsymbol{Forces}_l = m_l \cdot \boldsymbol{a}_{G_l} \tag{1}$$

- During the single support phase we recursively solve the linear form of Newton's second law from free effectors (foot not in support and hands) to the support foot. Since only the gravity acts on the free limbs as an external force, we can solve the equation for these limbs and calculate the force acting on the next limb, and so on.

- When the character is in the double support phase, the previous algorithm cannot be directly applied because the two ground reaction forces $\boldsymbol{FR}_1$ and $\boldsymbol{FR}_2$ are unknown. But the acceleration of the centre of gravity G of the whole system leads to the equation:

$$\boldsymbol{FR}_1 + \boldsymbol{FR}_2 + (-\boldsymbol{g}) \cdot \sum m_l = \left(\sum m_l\right) \cdot \boldsymbol{a}_G \qquad (2)$$

  where $(-\boldsymbol{g}) \cdot \sum m_l$ is the total weight of the character. To solve this equation with two unknowns, we use the angular expression of Newton's law expressed at point G:

$$\boldsymbol{GO}_1 \times \boldsymbol{FR}_1 + \boldsymbol{GO}_2 \times \boldsymbol{FR}_2 = [I]_G \cdot \dot{\boldsymbol{\omega}}_G \qquad (3)$$

  where O_1 and O_2 are the known positions of support, $[I]_G$ the inertia matrix and $\dot{\boldsymbol{\omega}}_G$ the angular acceleration vector. The angular momentum term is equal to zero because there is no localised momentum at these support points. With these two equations we are able to compute the ground reaction forces and then iteratively solve the linear equation from supports to hips.
- During a flying phase (no support), the computation is straightforward. Since there is no additional force, we then solve for the chains independently from free segments to the trunk. This case is useful for running movements and jumps. We thus obtain the internal forces for any locomotion style.

Angular form of Newton's second law:

The summation of external torques acting on a limb l is equal to the rate of change of its angular momentum:

$$\sum_j (\boldsymbol{G}_l\boldsymbol{O}_j \times \boldsymbol{F}_{j/l}) + \sum_j \boldsymbol{C}_{j/l} = [I]_{G_l} \cdot \dot{\boldsymbol{\omega}}_{G_l} \qquad (4)$$

where O_j is the application point at joint j of the external force $\boldsymbol{F}_{j/l}$ acting on l, and $\boldsymbol{C}_{j/l}$ is the angular momentum at O_j. We use an iterative algorithm to solve the angular equation at each articulation.

6 Experimental results

We have finally reached our analysis objective that is to compute the resulting forces and torques at joints. In this section, we answer the questions presented in Sect. 3, with a special focus on the ground reaction forces (GRF).

6.1 Self-coherent validation

The first question was: are the adapted motions physically valid? To answer this question, we apply "direct" adaptations, i.e. we apply the retargeting on a known real morphology and we only use the real data of this character to interpolate the motion. Figure 2 shows the comparison of the GRF of such direct adapted motions with force plate measurements of the same characters. In this figure, the black plots are three ground reaction forces (in newtons) measured by force plates for these characters and the blue plots are the analysed ground reaction forces from normal locomotion with the biomechanical data of the same characters.

The experimental measurements show that the first character (left part of the figure) produces an almost constant GRF, related to an immutable style of locomotion. Our direct adaptation process has no difficulties reproducing the same movement and thus the same GRF. In the second experiment (centre part), the style of the capture locomotion is variable; the adapted GRF thus have identical local maxima but different characteristics of the motion (see Sect. 6.3). The third experiment (right part) shows irregular captured GRF, the resulting adapted force is different while remaining valid on the maximum amplitudes. This result is probably due to the shifting of velocity.

In comparison with data described in the literature [2, 16], we notice, for example, that the vertical force

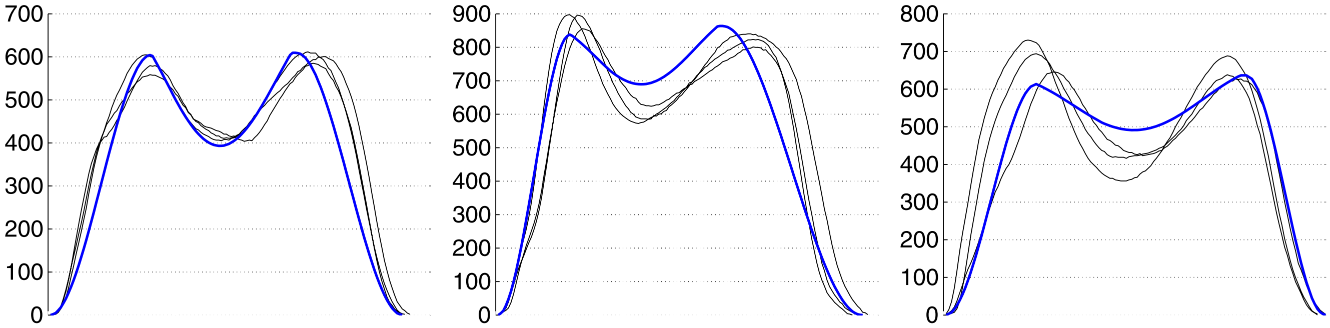

Fig. 2. From *left* to *right*: a 55.4 kg man, a 79.6 kg man, a 58.2 kg woman

shows the double hump generally observed in biomechanics, and exceeds body weight at two different times during the stance phase. The support duration also conform to these data. Validation on forces and torques at all joints have also been performed. These studies lead us to assume that our process answers positively to our first question concerning the physical correctness of the adapted motions.

Let us now recall the next two questions: what are the limits of the method, and are these limits due to the retargeting or to the interpolation? To address this point, we focus on the influence of the global scale of the characters and the influence of the character structure.

6.2 Influence of retargeting

In order to study the influence of retargeting on the physical realism of the adapted motion, we observe the resulting forces when we change the morphology of the targeted character. Therefore, this study recovers how the retargeting algorithm changes the physics of the motion, but has no relation to how the real physics change when the morphology changes. For that, we plan to capture locomotion and foot strike force data for real subjects corresponding to the changed physical parameters.

6.2.1 Global scale

We retarget one non-interpolated motion on eight different morphologies and examine the GRF (Fig. 3a). All limbs are scaled from half to double the size of the initial skeleton. Results shows that the global size of the character has a huge influence on the dynamics, indeed the masses are the main parameters in Eq. 1. In order to be able to compare these GRF, we have to normalize them. We looked for the relation between the scale on the morphology and the scale on the GRF minimising the root mean square (RMS) cumulated error (order 1). We show this relation in Fig. 3b, and we observe that this relation is a linear function (correlation coefficient = 0.87). We also compare the GRF with experimental data of real characters. We verified this relation by experimental data on several locomotions and subjects between 0.7 and 1.2 scales. Under 0.7 and over 1.2, we suppose that this relation is still valid.

6.2.2 Structure of the skeleton from degrees of freedom

In this section, we change the structure of the skeleton. We retarget one locomotion on two skeletons with 38 and 26 degrees of freedom (dof). They differ by the following articulations: elbows, knees and ankles, where the spherical joints (3-dof) become pin joints (1-dof). This leads to a reconstruction average difference of 2.0 cm per limb between the two structures. In order to study the significance of this value, the resulting GRF are plotted in Fig. 4a, and we present in Fig. 4b the RMS errors between the GRF of the two retargeted motions.

The lateral error is very small and this is logical because during locomotion the linear acceleration of limbs on this axis is low. If we retarget a locomotion on a more restrictive skeleton (fewer dof), the influence on the fore-aft axis is more important than on the vertical axis. Thus when we retarget a motion, we must be careful of the fore-aft acceleration of limbs. In this example, the higher GRF difference is equivalent to a modification of the weight of the character by 2.5 kg.

6.3 Influence of different modifications

As these results have been extensively presented in [11], we limit the presentation to a summarised version of these results.

The influence of the relative lengths of limbs is useful to evaluate the initial errors in the articular centres estimations. This influence is related to the retargeting part of the process. For example, the influence of femur/tibia length ratio while maintaining the global length of the leg is one of these possible variations. The standard value of this ratio is 0.95. We have performed variations on this ratio between 0.7 and 1.3 and have shown that be-

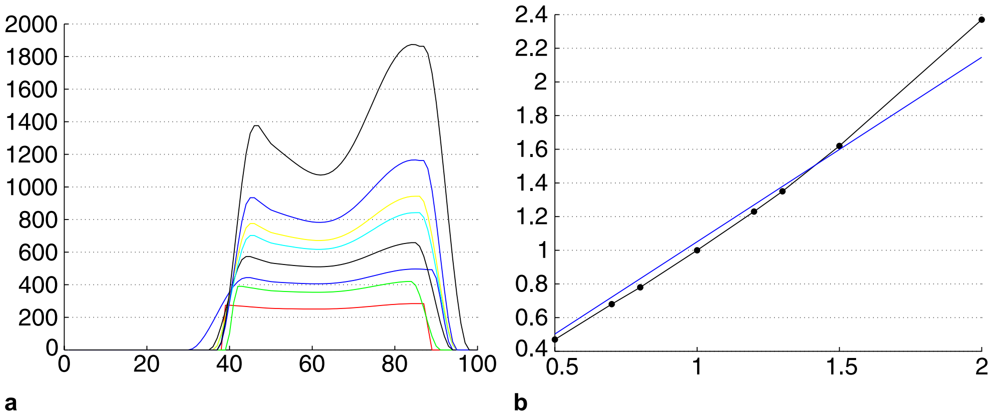

Fig. 3. Influence of a global scale. We retarget one locomotion on eight morphologies: ×0.5, ×0.7, ×0.8, ×1.0, ×1.2, ×1.3, ×1.5 and ×2.0. The resulting GRF (in newtons) are linearly dependent of the scale

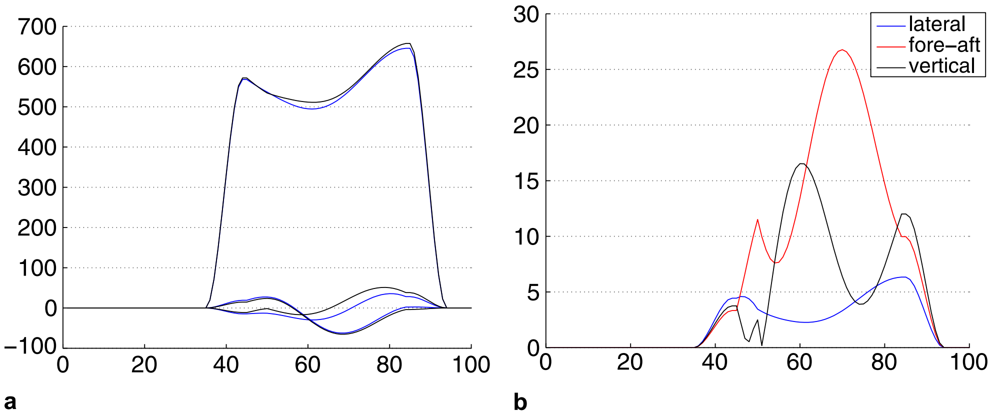

Fig. 4. Influence of the structure of the skeleton. We plot the 3D GRF (*blue*: the 38-dof model; *black*: the-26 dof model) and their RMS errors during the locomotion cycle

side these limits the RMS errors for the GRF are quite small. Namely, they are less than 3 newtons. Therefore, a loss of accuracy in the estimation of the articular centres does not lead to a loss of accuracy in the produced forces and torques. We also pointed out that the movements of the heaviest limbs are the most influenced. This influence can easily be observed by changing the upper/lower body ratio as the trunk represents 43% of the total mass of the body.

In order to study the influence of the interpolation on the physical realism of the adapted motion, we have also studied the GRF when changing locomotor parameters of the motion.

When we want the virtual human to follow foot-prints, we can modify the step size. The influence of the modification of the step size can also be useful to evaluate the footskate corrections that are often used in adaptation methods. These corrections are mainly based on changes of articular trajectories by using inverse kinematics methods and lead to the modification of the position of the foot and the length of the step. We have varied the initial step size within a range from 0.7 (70%) to 1.5 (150%). Besides these limits, the ground reaction forces are comparable to the initial ones because these steps are represented in the initial database. Outside these limits, the results are not valid because the motion is not represented in the initial database.

One of our applications was the study of a plausible walk for extinct hominids [12]. To this purpose, we have performed modifications on the rest posture of the character, which is driven by the erect percentile. When the variation of this erect percentile is less than 1 (corresponding to rest posture) and more than 0.8 (80%), the motion is performed in a bent style and the results show no significant disturbances on the ground reaction forces. On the contrary, when the variation of the erect percentile is more than 1 (the test has been performed until a value of 120%), the motion is performed in a more erected style and the disturbances are important. Namely, high erect postures prevent large steps. The conclusion of these tests is that interpolating to less erect styles of locomotion is safer.

The variation of the velocity of the walk is also an important parameter. The chosen range related to the initial velocity is between 0.67 and 1.33. The results have shown that the more the speed decreases, the more the error increases. In this case, the physical properties are preserved. On the other hand, when the speed increases, the amplitude of the double hump during the support phase increases up to invalid values. At this time, the interpolation process must change the motion style to a running locomotion (not managed in our approach).

7 Forward dynamics-based synthesis

The method of inverse dynamics presented in the previous section allows for the evaluation of the physical realism of locomotion. We obtain, after the resolution, the resulting forces and torques that generate the motion. Now, we want to study the possibility of using these data to synthesize, by forward dynamics, new physically valid motions.

Additionally, as we normalized the representations of the character and the motion during the kinematical adaptation process, we define a normalization of the resulting forces and torques for the dynamics-based synthesis. The proposed approach consists in associating forces/torques to morphologies and styles of motion. We choose these parameters because our analysis shows that they have the most influence on the physical properties of locomotion. In the following section we present the relations that we have observed between these data (in Sect. 7.1) and their applications on preliminary virtual human simulations (in Sect. 7.2).

7.1 Force and torque normalizations

We study the relations between the forces/torques, the morphologies and the styles of motion by examining the possible combinations. For example, we want to know if motions from the same character and the same style produce the same normalized forces/torques. Similarly, we want to evaluate such forces using several motions performed by the same character, using the same style of motion performed by different characters, and using different styles performed by several characters. To answer these questions, we compare, thanks to statistical evaluations, each value of force/torque. We use and note these evaluations as follows:

- RMS(p) is the Root Means Square error of p order.
- E.A is the average value of Euclidian distances.
- CC.A is the average value of correlation coefficient.
- Deriv. is the average first time derivative.

The RMS and E.A methods compute the distance between the sets, i.e. their absolute difference. The CC.A and Deriv. methods compute their resemblance, i.e. their relative difference.

We present here, the evaluation of the normalization on a small set of motions (see Table 1). The E_1 motion is our reference motion, and we want compare it with erect E and bent B motions of the same (Character 1) and one other character (Character 2). The mass of Character 1 is 74.0 kg and the mass of the Character 2 is 69.7 kg. We use these values to normalize the forces and torques, and present here results for the ground reaction forces (highest values of the external forces). To demonstrate the interest of the normalization, we present two results. The first one is the kinematical difference between the motions, and the second one is the difference between the normalized GRF.

In Fig. 5, we represent the kinematical difference between the motions thanks to the trajectory of the root node of the character (middle of the pelvis). This trajectory is characteristic of the motion and includes a large variation, so easily evaluable, of its vertical component according to the style of the motion. Table 2 shows the evaluation of the differences between the reference motion and the others.

Table 1. Study of the normalization validity on a set of five motions

	Character 1	Character 2
Erect	E_1,E'_1	E_2
Bent	B_1	B_2

We observe that motions with the same style have only small differences (E_1,E'_1 and E_2) and that E_2 is much closer to E_1 than B_1. This means that the trajectory of the root depends more on the style than on the morphology of the character. Moreover, we assert that B_2 is very distant from the reference erect locomotion E_1 (different style and morphology).

Now, to illustrate the force/torque normalization, we show the normalized GRF on the same motions and we evaluate them using the same statistical criteria. Figure 6 shows the 3D components of the normalized GRF and Table 3 presents the differences between the reference GRF and the others. The most important result is shown by the E_2 evaluation. Indeed, the distance and the resemblance with the reference motion are very similar to E'_1, the motion representing the average reproducibility

Table 2. Differences between the root trajectory of E_1 and the others

	E_1	E'_1	B_1	E_2	B_2
RMS(1)	0.0	0.234	0.621	0.512	1.001
E.A	0.0	0.026	0.068	0.056	0.109
CC.A	1.0	0.973	0.681	0.980	0.399
Deriv ($\times 10^{-4}$)	0.0	12.0	23.0	6.4	42.0

Table 3. Differences between the normalized GRF of E_1 and the others

	E_1	E'_1	B_1	E_2	B_2
RMS(1)	0.0	0.150	0.426	0.141	0.946
E.A	0.0	0.025	0.071	0.026	0.148
CC.A	1.0	0.938	0.826	0.954	0.702
Deriv ($\times 10^{-3}$)	0.0	36.5	74.1	37.3	162.2

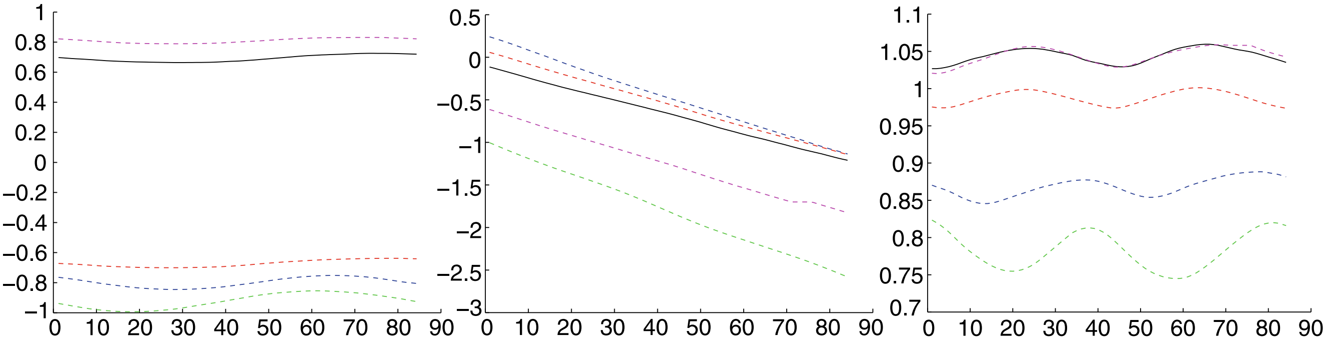

Fig. 5. Lateral, horizontal and vertical components of the root node. E_1 in *black*, E'_1 in *violet*, B_1 in *blue*, E_2 in *red* and B_2 in *green* (x-axis is the frame time, y-axis is the 3D positions in meters)

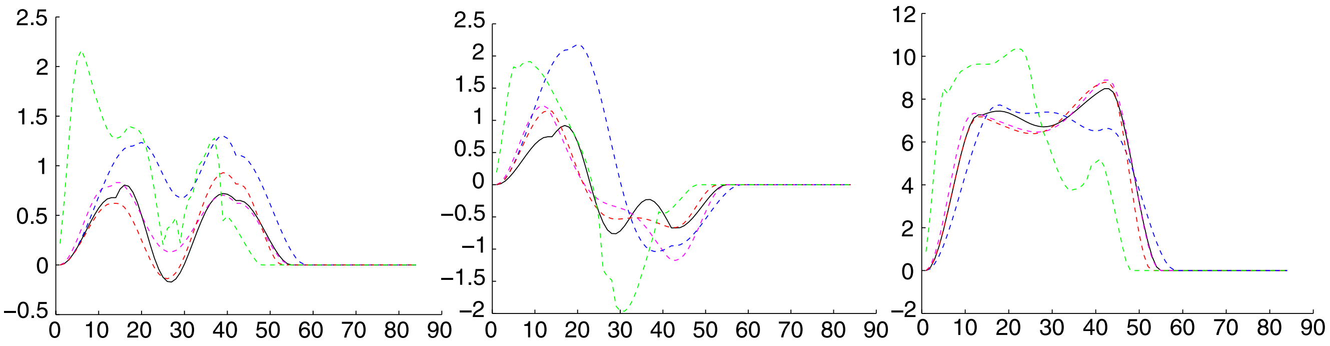

Fig. 6. Lateral, horizontal and vertical components of the normalized GRF. E_1 in *black*, E'_1 in *violet*, B_1 in *blue*, E_2 in *red* and B_2 in *green*

of the reference motion. Normalized GRF from different characters are therefore, here, quite similar to the GRF from the same character for a specific style of motion. We demonstrate it in our small set of motions, but we cannot say that the normalization is valid on any locomotion of the same style or for any style. Therefore, we plan to do conduct these evaluations on the entire database.

7.2 Preliminary results

The method of motion synthesis thanks to force/torque control can be solved by the forward dynamics approach. Rigid body mechanics uses scientific models, which provides answers and algorithms for this approach. We use such models and algorithms through a mechanical library, called NMecam [4]. This library simulates the physical motion of polyarticulated rigid bodies thanks to the automatic computation and resolution of the laws of motion applied on a specific system.

We only provide to the process the following parameters:

- The mechanical model: rigid bodies with masses and inertias, and links
- The initial state of the system: values of the dof and their first time derivate
- The external forces: gravity and GRF
- The motor torques: coming from the dynamics-based analysis and the normalization

All of these parameters are extracted from the inverse dynamics approach, the creation of the system is then automatic.

Our first results on human locomotion (see Fig. 7) are obtained as the combination of independent motions of the limbs. The limbs of the character are analysed as independent rigid bodies. Then, the forces/torques are used to synthesize new motions on other characters thanks to the normalization and the forward dynamics method.

8 Conclusion

The topic of this paper is the study of human locomotion using analysis and synthesis approaches. We have presented a method of dynamics-based analysis of retargeted and interpolated locomotions with the aim of validating the used adaptation algorithm. In this method, we first define the human model as a biomechanical representation of the character. This representation is created by improving a given mechanical model of the skeleton using anthropometrical tables and regression laws. The second stage consists in defining a transformation process, which enables us to work with a joint-angle motion. Finally, using support phase recognition, we check the correctness of the forces and torques with special attention to the ground reaction forces. The resulting forces/torques can then be normalized by the morphology and used in order to synthesize new motions using a dynamics-based synthesis.

This process is automatic, generic and independent of the adaptation method. Our analysis estimates how the adaptation method changes the dynamics of the motion. We have compared the results with real data, but it is not sufficient to prove that the adaptation method is valid with any required constraints. We need more experimental data

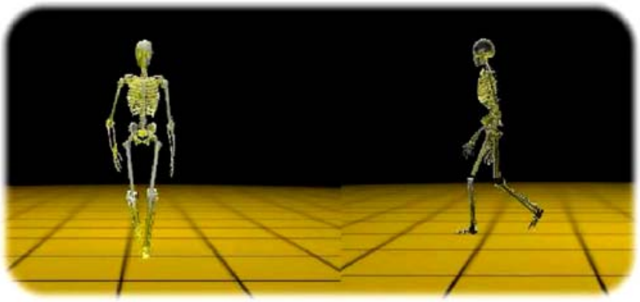

Fig. 7. The simulation of a human locomotion with normalized forward dynamics on the same character. The synthesized motion (in *grey*), is very close to the original motion (in *yellow*)

such as motor torques and ground reaction forces, and we potentially need to overcome the standard limitation of the dynamics-based approach (such as the uniform distribution of masses or the joint friction) to improve our inverse and forward dynamics algorithms. More experiments on the forward dynamics-based synthesis using the morphological normalization will be performed, extending the example to the whole database. The three components of the approach (motion adaptation, inverse dynamics analysis and forward dynamics synthesis) are complementary and independent. One of the most interesting future works would be consequently to apply our methods to approaches using other adaptation algorithms and different synthesis methods.

References

1. Abe, Y., Liu, C.K., Popović, Z.: Momemtum-based parametrization of dynamic character motion. In: ACM Siggraph/Eurographics Symposium on Computer Animation, pp. 173–182, August 2004
2. Apkarian, J., Naumann, S., Caims, B.: A three-dimensional kinematic and dynamic model of lower limb. J. Biomechanics **22**, 143–155 (1989)
3. Arikan, O., Forsyth, D.A., O'Brien, J.F.: Pushing people around. In: ACM Siggraph/Eurographics Symposium on Computer Animation, pp. 59–67, July 2005
4. Arnaldi, B., Dumont, G., Hégron, G.: Dynamics and unification of animation control. Vis. Comput. **5**(1–2), 22–31 (1989)
5. Bindiganavale, R., Badler, N.I.: Motion abstraction and mapping with spatial constraints. Lect. Notes Comput. Sci. **1537**, 70–82 (1998)
6. DeLeva, P.: Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J. Biomechanics **29**(9), 1223–1230 (1996)
7. Hodgins, J.K.: Animating human motion. Sci. Am. **278**(3), 64–69 (1998)
8. Khalil, W., Kleinfinger, J.: A new geometric notation for open and closed loop robots. In: ICRA'86, pp. 75–79, April 1986
9. Ko, H., Badler, N.I.: Animating human locomotion with inverse dynamics. IEEE Comput. Graph. Appl. **16**(2), 50–5 (1996)
10. Popović, Z., Witkin, A.: Physically based motion transformation. In: Proceedings of SIGGRAPH'99, pp. 11–20, August 1999
11. Pronost, N., Dumont, G.: Validating retargeted and interpolated locomotions by dynamics-based analysis. In: 4th International Conference on Computer Graphics and Interactive Techniques in Australasia and South-East Asia (GRAPHITE 2006), Kuala Lumpur, Malaysia, pp. 65–74 (2006)
12. Pronost, N., Dumont, G., Berillon, G., Nicolas, G.: Morphological and stance interpolations in database for simulating bipedalism of virtual humans. Vis. Comput. **22**(1), 4–13 (2006)
13. Safonova, A., Hodgins, J.K.: Analyzing the physical correctness of interpolated human motion. In: ACM Siggraph/Eurographics Symposium on Computer Animation, pp. 171–180, July 2005
14. Tak, S., Ko, H.: A physically-based motion retargeting filter. ACM Trans. Graph. **24**(1), 98–117 (2005)
15. Van de Panne, M., Fiume, E., Vranesic, Z.G.: Control techniques for physically-based animation. In: Proceedings of the Third Eurographics Workshop on Animation and Simulation (1992)
16. Vaughan, C.L., Davis, B.L., O'Connor, J.C.: Dynamics of Human Gait, 2nd edn. Kiboho, Cape Town, South Africa (1999)
17. Yamane, K., Nakamura, Y.: Dynamics filter – concept and implementation of on-line motion generator for human figures. IEEE Trans. Robot. Autom. **19**(3), 421–432 (2003)
18. Zhao, J., Badler, N.I.: Inverse kinematics positioning using nonlinear programming for highly articulated figures. ACM Trans. Graph. **13**(4), 313–336 (1994)
19. Zordan, V.B., Hodgins, J.K.: Motion capture-driven simulations that hit and react. In: SCA'02: Proceedings of the 2002 ACM SIGGRAPH/Eurographics Symposium on Computer Animation, pp. 89–96 (2002)
20. Zordan, V.B., Majkowska, A., Chiu, B., Fast, M.: Dynamic response for motion capture animation. ACM Trans. Graph. **24**(3), 697–701 (2005)

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