Motion Retargeting for Virtual Human Based on Vector Features of Lower Limbs

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Abstract. In view of the contradiction that limited motion data can not meet the requirements of rich and changeable motion, motion reuse technology emerges as the times require, which can drive different human skeleton models with the same motion data to generate corresponding motion. However, when the motion data is used to drive the human models with different heights and bone proportions, motion deformation often occurs. In order to solve this problem, the concept of human lower limb vector is proposed in this paper. By analyzing human motion, it is pointed out that the lower limb vector can maintain the main characteristics of motion, and then a human motion redirection method based on the invariance of lower limb vector feature is proposed. This method can redirect the motion data from the original bone model to the target bone model with different bone length ratio, while maintaining the main characteristics of the original motion. The experimental results show that this method has good motion redirection effect and fast computational efficiency.

Keywords. Virtual human; motion retargeting; motion feature.

1. Introduction
The method of human motion generation based on data-driven has the advantages of easy realization and high fidelity of generated motion. The key of human motion generation based on data-driven is the acquisition of motion data. The commonly used method is motion capture method, which captures the motion information of performers through the motion capture equipment. Motion data has a strong pertinence. A given segment of motion data is often bound to a human skeleton model with fixed topology and bone length. When the motion data is used to drive other human skeleton models, motion distortion will occur. This feature of motion data restricts its wide application, because it is impossible to capture the motion of all human bodies with different bone lengths. In order to solve this problem, people began to study the processing technology of motion data, hoping to process the motion data of the original human skeleton model, so that it can correctly drive the target human skeleton model, and maintain the main motion characteristics, which is motion redirection technology.

According to the different solutions, the implementation methods of motion redirection can be divided into inverse kinematics (IK) based methods, space-time constraints based methods and physical constraints based methods. The method based on IK is the most basic motion editing technology. Its basic idea is to first determine the position constraint of the end effector of the target bone model according to the motion capture data and the relationship between the target bone model and the original bone model, and then the IK solver calculates the motion data of the middle joint, so as to get the new motion. Gleicher et al. [1] applied the spatiotemporal constraint method to motion redirection. They designed a spatiotemporal constraint solver. By optimizing the solution, a lot of
calculation time was avoided, the solution speed was improved, and the original motion quality was maintained. The above motion redirection methods usually only consider the geometric position constraints of human motion, but not the physical constraints, so they are not suitable for sports with high dynamic performance, such as jumping, boxing, table tennis and so on. Tak et al. [2] think that balance is an important physical characteristic that makes human motion natural and real, and propose a motion balance filtering method, they think that balance constraint is an important physical constraint. Pullen et al. [3] extended the scope of physical constraints, including moment constraints and momentum constraints in addition to balance constraints. They transformed motion redirection into constraint state estimation based on frame by frame Kalman filter. Tak et al. [4] further added dynamic and kinematic constraints, and realized the physical based motion redirection method using Kalman filter, and applied for the US national patent for this method [5].

In this paper, a method of motion redirection for human lower limbs is proposed, which keeps the main characteristics of the retargeted backward motion through the vectors of lower limbs, avoiding the motion distortion phenomenon. At the same time, the efficiency of motion redirection is high because there is no complex operation.

2. Motion Distortion
Because of the strong pertinence of the motion data, when the same motion data is used to drive the human body of different sizes directly, the motion distortion will occur. For the lower limbs of human body, the common motion distortion mainly includes suspension, ground penetration, sliding, drift and motion deformation.

Figure 1 shows the penetration or suspension distortion caused by directly driving different sizes of human body with the same motion data. In the figure, (a) is normal motion, (b) is the distortion of lower limbs penetrating the ground when driving the human body model with longer bone length with the motion data, (c) is the distortion of human body suspension when driving the human body model with shorter bone length with the motion data.

![Figure 1. The phenomenon of penetration or suspension distortion.](image)

Figure 2 shows the slide or drift distortion caused by using the same motion data to directly drive the human body of different sizes. The motion data in the figure is the action of standing on the right leg and retracting the left leg during walking. In this process, the position of the right foot should always be the same. In the figure, (a) is the normal motion, and (b) is the right foot backward when using the motion data to drive the human body model with longer bone length. The distortion phenomenon of sliding step, (c) is the distortion phenomenon that the right foot drifts forward when using the motion data to drive the human body model with shorter bone length. In order to show the distortion clearly, the right lower limb of human body is marked with black, and the rest is marked with gray.

In addition, the phenomenon of motion distortion also includes motion distortion, which refers to the phenomenon that the motion data drives the body model with inappropriate size, resulting in the distortion of the motion posture and the unreality.
Figure 2. Slide or drift distortion caused by direct driving of human body of different sizes.

3. Human Lower Limb Vector
In order to maintain the main characteristics of the motion, we propose the concept of human lower limb vector in the process of motion redirection. The lower limb vector refers to the vector from the thigh root to the heel, which has the characteristics of length and direction. The length of the lower limb vector is the distance from the thigh root to the heel, and the direction of the lower limb vector is from the thigh root to the heel. As shown in figure 3, the lower limb vector includes the right lower limb vector r and the left lower limb vector L. Introducing the lower limb vector, we can study the thigh and the lower leg as a whole, that is, a bone with variable length. In the human skeleton model, the position of the hip bone relative to the root node is fixed. When the root node and the lower limb vectors L and R are determined, the position of the foot can be directly obtained. Therefore, the lower limb vectors establish the direct position relationship between the foot and the root node, making the adjustment of the foot position more intuitive and simple, and also convenient to calculate the position of the root node from the foot position. At the same time, after the length and direction of the lower limb vectors L and R are determined, it is easy to calculate the joint rotation angle of the thigh and the lower leg using geometric method.

Figure 3. Lower limb vector.

4. Algorithm Principle
For the first kind of motion, when the target bone model and the original bone model have the same bone length ratio, the motion data can be directly assigned to the target bone model, and then the root node of the target bone model can be translated to achieve motion redirection without distortion. As shown in figure 4, a walking motion data is redirected, in which the higher bone model is the original bone model, and the shorter bone model is the target bone model. The length of all bones in the target bone model is 60% of the corresponding bone of the original bone model, that is, they have the same bone length ratio, and only the global position of the root node is redirected. Translation processing, it can be seen from the figure that the effect of motion redirection is better.
In general, the target bone model and the original bone model do not have the same bone length ratio. If only the global position of the root node is translated during the motion redirection, the distortion phenomenon will occur. It is necessary to continue to adjust the position of the foot. Adjusting the position of the foot can be achieved by adjusting the length and direction of the lower limb vector. The method of adjusting the lower limb vector is to keep the lower limb vector feature unchanged. In the process of motion redirection, the lower limb vector feature unchanged means that the length feature and direction feature do not change, including the following two aspects:

![Figure 4. Motion redirection with the same bone length proportion.](image)

1. The direction feature of the lower limb vector is unchanged, which means that the direction of the lower limb vector does not change before and after redirection, and the two can be overlapped by translation.

2. The length feature of the lower limb vector remains unchanged, which means that the ratio of the length of the lower limb vector does not change with time before and after redirection, that is, the ratio of the vector length of the front lower limb to the vector length of the back lower limb is constant.

As shown in figure 5, \( L_i \) and \( L_{i+k}^{'} \) are the left lower limb vectors of frames \( i \) and \( i + k \) in the original motion, \( L_i' \) and \( L_{i+k}^{''} \) are the left lower limb vectors of frames \( i \) and \( i + k \) after resetting. Adjust \( L_i' \) and \( L_{i+k}^{''} \) to keep the vector direction and length characteristics of the left lower limb unchanged before and after the redirection, that is, \( L_i \) and \( L_i' \) directions are the same, \( L_{i+k} \) and \( L_{i+k}^{''} \) directions are the same, and \( |L_i'| / |L_i| = |L_{i+k}^{'}| / |L_{i+k}| \). According to the knowledge of space geometry, when \( r_{r_{i+k}}^{r_{i+k}} \) and \( r_{r_{i+k}}^{r_{i+k}^{''}} \) are in the same direction and \( |f_{r_{i+k}}^{r_{i+k}}| / |f_{r_{i+k}}^{r_{i+k}^{''}}| = |L_i'| / |L_i| \), \( f_{r_{i+k}}^{r_{i+k}} \) and \( f_{r_{i+k}^{''}}^{r_{i+k}^{''}} \) are in the same direction and \( |f_{r_{i+k}}^{r_{i+k}}| / |f_{r_{i+k}^{''}}^{r_{i+k}^{''}}| = |L_i'| / |L_i| \). In this case, quadrilateral \( r_{r_{i+k}}^{r_{i+k}}f_{r_{i+k}}^{r_{i+k}}f_i \) and quadrilateral \( r_{r_{i+k}}^{r_{i+k}^{''}}f_{r_{i+k}^{''}}^{r_{i+k}^{''}}f_i^{''} \) are similar quadrilateral, that is, the corresponding angles are equal and the corresponding edges are proportional. It can be seen that keeping the characteristics of the lower limb vector unchanged before and after redirection can ensure that the displacement of the root node and the displacement of the foot have the same rate of change between any two frames, which are equal to the rate of change of the length of the lower limb vector. In this case, the root node of the target skeleton model is translated according to the ratio of the length of the lower limb vector in the same frame before and after redirection, which can effectively avoid the distortion phenomena such as suspension, penetration, sliding and drift.

On the other hand, in the process of motion redirection, by keeping the vector characteristics of the lower limbs unchanged, the retargeted backward motion can still keep the original main motion characteristics. As shown in figure 6, the left side is the original jumping and kicking motion, and the right side is the motion after redirecting the motion data to a smaller human skeleton model. In the process of redirection, the vector characteristics of the lower limbs are kept basically Unchanged, the dotted arrow in the figure is the lower limb vector. It can be seen from the figure that the retargeted backward movement still maintains the main motion characteristics of the jump kick.
5. Retargeting Algorithm

The motion redirection algorithm based on the invariable feature of the lower limb vector mainly includes the following six steps:

Step 1. Assign the original motion data to the target bone model directly, which will cause motion distortion.

Step 2. Determine the scale factor scale according to the size relationship between the target bone model and the original bone model. Scale is used to adjust the root node and the lower limb vector of the target bone model.

\[
\text{scale} = \frac{l_{\text{target}}}{l_{\text{source}}} \tag{1}
\]

Among them, \(l_{\text{source}}\) represents the sum of the length of the thigh bone and the calf bone of the original skeleton model, and \(l_{\text{target}}\) represents the sum of the length of the thigh bone and the calf bone of the target skeleton model. After the scale \(\text{scale}\) is determined, the root node and the lower limb vector of the target skeleton model can be adjusted. The global position of the root node of the original skeleton model is represented by \(\text{Root} = \{r_i|i=1...n\}\), where \(r_i = (x_i, y_i, z_i)\) and \(i\) are frame numbers, and there are \(n\) frames of motion data. The global position of the root node of the retargeted bone model is represented by \(\text{Root}' = \{r'_i|i=1...n\}\), where \(r'_i = (x_i, y_i, z_i)\), \(i\) is the frame number. The position of the

Figure 5. Motion redirection with invariable vector characteristics of lower limbs.

Figure 6. The maintenance of motion features by keeping the vector features of lower limbs unchanged.

Step 3. Adjust the position of the root node of the target bone model.

Step 4. Adjust the length and direction of the lower limb vector of the target skeleton model, and then adjust the joint angle of the lower limb.

Step 5. Adjust the orientation of the target bone model foot to keep it consistent with the original bone model.

Step 6. Adjust the position of the root node of the target bone model.
The root node of the target skeleton model is adjusted according to the following formula (for example, the adjustment method of Y coordinate and Z coordinate is the same as that of X coordinate):

\[
\begin{align*}
    x'_i &= x_i \cdot \text{scale} & i = 1 \\
    x'_i &= x'_{i-1} + (x_i - x_{i-1}) \cdot \text{scale} & i = 2 \ldots n
\end{align*}
\] (2)

The adjustment of the lower limb vector includes two aspects: one is the adjustment of the lower limb vector length to make it scale according to the scale factor 1; the other is the adjustment of the lower limb vector direction to keep it consistent with the lower limb vector direction of the original skeleton model. As shown in Figure 7, take the adjustment of the left lower limb vector as an example. In the figure, \( L_i \) is the left lower limb vector in the original skeleton model, \( L'_i \) is the left lower limb vector after the motion data is directly assigned to the target skeleton model. The adjustment of the left lower limb vector is to adjust the length and direction of \( L'_i \) to meet the requirements.

![Figure 7. Schematic diagram of lower limb vector adjustment.](image)

Assuming that the length of the left leg vector \( L_i \) in the original skeleton model is \( d_i \), the length \( d'_i \) of the left leg vector \( L'_i \) in the target skeleton model is adjusted to:

\[
d'_i = d_i \cdot \text{scale}
\] (3)

Since the length \( l_{\text{up}} \) of the thigh bone and the length \( l_{\text{down}} \) of the calf bone in the target bone model are both known, the included angle \( \alpha \) at the knee can be calculated from the cosine theorem as follows:

\[
\alpha = \arccos \left( \frac{l_{\text{up}} \cdot l_{\text{up}} + l_{\text{down}} \cdot l_{\text{down}} - d'_i \cdot d'_i}{2 \cdot l_{\text{up}} \cdot l_{\text{down}}} \right)
\] (4)

In order to adjust the direction of lower limb vector \( L'_i \) to be in the same direction as \( L_i \), it is necessary to calculate the included angle \( \beta \) between \( L'_i \) and \( L_i \), which can be calculated by the following formula:

\[
\beta = \arccos \left( \frac{L_i \cdot L'_i}{|L_i| \cdot |L'_i|} \right) = \arccos \left( \frac{L_i \cdot L'_i}{d'_i \cdot d'_i} \right)
\] (5)

where \( L_i \cdot L'_i \) is the point multiplication of vector and \( |L_i| \) is the modulus of vector.

Because the rotation angles of thigh and calf have been adjusted, the direction of foot will also change. It is necessary to adjust the direction of foot in the target bone model to make it the same as that in the original bone model. The direction of foot can be adjusted by adjusting the direction of lower limb vector. After adjusting the direction of the foot, the distance between the toe position and the constraint surface will change. Therefore, it is necessary to adjust the height of the root node so
that the closest distance between the toe and the constraint surface remains the same as in the original motion. Therefore, increase the root node of all data frames by $\Delta$ in the vertical direction:

$$\Delta = \min(D_i) - \min(D'_i) \quad i=1,2,...n$$

Among them, $D_i$ represents the distance between the toe of the $i$th frame of the original motion data and the constraint surface, $D'_i$ represents the distance between the toe of the $i$th frame after adjusting the direction of the foot and the constraint surface, $\Delta > 0$ represents the height of the raised root node, and $\Delta < 0$ represents the height of the lowered root node.

6. Experimental Results and Analysis

In order to verify the correctness and effectiveness of the algorithm in this chapter, we have carried out a motion redirection experiment. In the experiment, the sample motion data is from the mocap human motion capture database of Carnegie Mellon University [6].

In this paper, we use the method of motion redirection based on the invariable vector characteristics of the lower limbs. The walking motion includes 340 frames. The length and proportion of the lower limbs of the original skeleton model and the target skeleton model are shown in table 1.

| Skeleton model | Leg length (m) | Thigh length (m) | Lower leg (m) | Length ratio |
|----------------|---------------|-----------------|--------------|-------------|
| Original       | 0.893         | 0.455           | 0.438        | 1.039:1     |
| Target         | 0.536         | 0.195           | 0.341        | 0.572:1     |

Figure 8 shows the result of redirection of walking motion from the original bone model to the target bone model, in which (a) is the original motion, and (b) the retargeted backward motion. The data of frames 146, 151, 156, 161, 166, 171, 176 are shown in the figure. As can be seen from the figure, motion redirection eliminates the distortion phenomena such as suspension, penetration, sliding and drift.

Figure 9 shows the trajectory of the left heel before and after the motion redirection. It can be seen from the figure that the trajectory of the motion retargeted backward is similar to the shape of the original trajectory, indicating that the motion retargeted backward maintains the main motion characteristics.

In order to compare the effect of motion redirection, we use space-time constraint method [2] and physical constraint method [7] to carry out the experiment of motion redirection, and compare the experimental results with the experimental results of this method. Table 2 shows the comparison between the method in this paper and the method based on spatiotemporal constraint. It can be seen from the table that compared with the method based on spatiotemporal constraint, the method in this...
paper has better effect of motion redirection, because in the process of motion redirection, in addition to spatiotemporal constraint on the human skeleton model, the method in this paper also considers the motion trajectory and the vector pair of lower limbs. The influence of motion and their preservation of motion features after motion retargeting.

Figure 9. Left heel track.

Figure 10 shows the comparison between the method in this paper and the method based on physical constraints in motion redirection efficiency. The figure shows the statistical curve of the calculation time of the redirection of the lower limbs of a dance movement changing with the number of motion frames. It can be seen from the figure that the method in this paper has higher calculation efficiency. With the increase of the number of motion data frames, the method in this paper basically changes linearly in motion redirection time. The time of motion reorientation based on physical constraints increases exponentially. This is because the method in this paper avoids the complex physical constraint model of human motion in motion redirection, but constrains the motion redirection from the perspective of motion geometry features, so it reduces the computation to a large extent.

Table 2. The comparison of motion redirection effect between our method and spatiotemporal constraint.

| Types of motion      | Frame number | Number of motion distortion frames (percentage) |
|----------------------|--------------|-----------------------------------------------|
|                      |              | Article method                                | Spatiotemporal constraint method |
| Long jump            | 453          | 8 (1.77%)                                     | 14 (3.09%)                     |
| Jump kick            | 352          | 4 (1.14%)                                     | 13 (3.69%)                     |
| Back somersault      | 426          | 7 (1.64%)                                     | 16 (3.76%)                     |

Figure 10. The efficiency comparison between the method in this paper and the method based on physical constraints.
7. Conclusion
In this paper, a method of motion retargeting for virtual human is proposed. According to the motion characteristics of human body, the concept of human lower limb vector is proposed. By keeping the length and direction characteristics of lower limb vector unchanged, the main features of the motion can still be maintained in the retargeted backward motion. Compared with the method based on space-time constraints, this method has better effect of motion redirection; compared with the method based on physical constraints, this method has faster computational efficiency.

Acknowledgment
This work is supported by the National Nature Science Funding No. 61602506, No. 11805278 and the Hu Bei Province Nature Science Funding No. 2016CFB307.

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