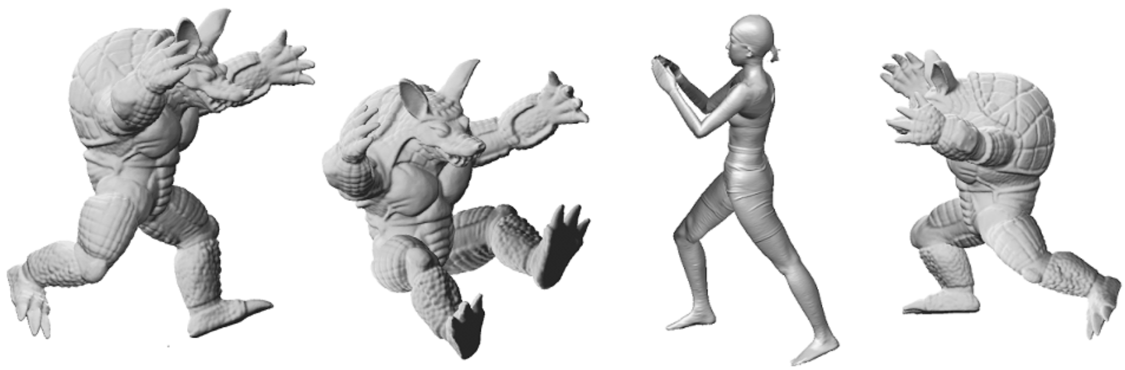
Modeling and Deformation of Arms and Legs Based on Ellipsoidal Sweeping

Dae-Eun Hyun, Seung-Hyun Yoon, Myung-Soo Kim, and Bert Jüttler



Abstract

We present a new approach to the modeling and deformation of a human or virtual character's arms and legs. Each limb is represented as a set of ellipsoids of varying size interpolated along a skeleton curve. A base surface is generated by approximating these ellipsoids with a swept ellipse, and the difference between that and the detailed shape of the arm or leg is represented as a displacement map. We demonstrate that the natural bending of arms and legs can be emulated using this approach, and show its effectiveness by articulating the limbs of a scanned human body and those of a virtual character.

Keywords: *Arm and leg modeling, motion-based modeling, swept volume, sweep surface, moving ellipse/ellipsoid, displacement map, multilevel B-splines.*

1 Introduction

Natural modeling and flexible deformation of the human body shape is a significant goal of three-dimensional free-form shape modeling. Early applications of body modeling and deformation were mainly found in computer-animated movies. Recent uses include character modeling and animation in three-dimensional games and virtual reality. In the near future, geometric models of the human body will play a crucial role in product design, allowing industrial products such as cars, furniture and clothing to be custom-designed for an individual's body shape.

In computer graphics, many advanced techniques [2, 5, 7, 12, 17, 18, 20, 24] have been developed for human body modeling and animation. Some recent approaches [1, 4, 9, 19] are based on range scanning and motion capture data, using data from a real human body in motion to achieve realistic animation of a model. However, to utilize these techniques successfully, a real body must be scanned in many different poses [1]. It would be convenient if there were a way to reduce the number of poses while maintaining the quality of the modeling and animation.

Biscoff and Kobbelt [3] introduced a multiresolution technique for approximating general free-form objects by a collection of ellipsoids. Additionally, Choi et al. [6] and Wang et al. [21, 22] presented efficient algorithms for detecting the collision or separation between two static or moving ellipsoids. These results suggest ellipsoids as a natural geometric prim-

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itive for the efficient modeling and processing of free-form shapes such as the human body.

In this paper, we propose a sweep-based technique for modeling the human arms and legs and their deformation. A limb is first approximated by the volume swept by an ellipsoid which changes its size as it moves. At a joint, the ellipsoid changes its direction and moves along the next rigid element of the arm or leg. Thus elbows and knees are approximated by ellipsoids, while the rigid parts of a limb are represented by tubular sweep surfaces. The difference between the original surface and this approximate base surface is then represented as a displacement map.

The remainder of this paper is organized as follows. Section 2 briefly reviews related work on human modeling and animation. In Section 3, we present an overview of our representation scheme. In Section 4, the main steps of our method are explained in detail. Some experimental results are presented in Section 5 and, in Section 6, we draw some conclusions.

2 Related Work

Advanced techniques for human body modeling and deformation can roughly be classified into three different approaches: layered-structure, anatomy-based, and example-based modeling.

Layered modeling techniques [5, 12, 18] represent the human body by geometric approximations of the skeleton, muscles, fatty tissues, and skin layer. Muscles and fatty tissues are often represented as simple primitives which can support fast deformation of an articulated body [12]. This layered approach greatly enhances the realism of a human body model, allowing smooth and naturalistic deformations.

Anatomy-based methods [2, 7, 17, 20, 24] create an accurate human body model based on a precise representation of the skeleton, muscles, and fatty tissues. These techniques generate realistic and dynamic deformation of an articulated body using physical simulation but, due to their high computational cost, applications are mainly in off-line simulation and animation.

Alternatively, actual human body shape and deformations can be generated using measured data, which may be obtained by techniques such as range scanning or motion capture. Many such techniques have been developed for facial animation [4, 9]. For instance, Talbot [19] used range scans to create articulated deformations of the arm and, in a more recent work, Allen et al. [1] proposed realistic articulated deformation of the upper body by interpolating the body shapes from a sequence of key poses. The body shapes between poses were reconstructed as a parametrically consistent displaced subdivision surface.

In this paper, we take a hybrid approach that imposes a simplified layered structure on a human model scanned at a single pose, or on an articulated polygonal model. By reconstructing the arms and legs of such a model in a sweep-based layered structure, we can deform the articulated body shapes smoothly and naturally. A single static pose covers many current applications of computer models of human and virtual characters. Thus the solution presented in this paper should find practical applications in smaller systems. Alternatively, our results may be used as a basic component in a complete system such as the one proposed by Allen et al. [1]. In future work, we aim to make our approach more compatible with other methods.

3 Framework of Our Approach

In this paper, we assume that the body of a human or a virtual character is given as a point cloud or a polygonal model. Arms and legs are reconstructed as a simple structure which consists of three layers: a skeleton, key ellipsoids, and skin. Skeletons are represented as line segments extracted from the input data and based on known features of arms and legs. Each arm or leg is then approximated by several key ellipsoids that best fit its interior volume. To make things simpler, we restrict ourselves to ellipsoids whose major axes are parallel to the local coordinate axes of the arm or leg, and are therefore translated and scaled copies of each other. The skin layer (wrapping around muscles or ellipsoids) is reconstructed in two sub-layers: (i) a base surface generated as a sweep envelope of the moving ellipsoid and (ii) a detailed surface represented as a map of displacements from the base surface to the original data.

Figure 1 shows an overview of our construction scheme. The details of each step can be summarized as follows.

1. *Segmentation and skeleton construction*
   We segment input data into arms, legs, and torso. Features such as elbows, knees, and ankles are automatically detected or their locations can be specified or modified by the user. A simple skeleton structure is then constructed based on these feature points.

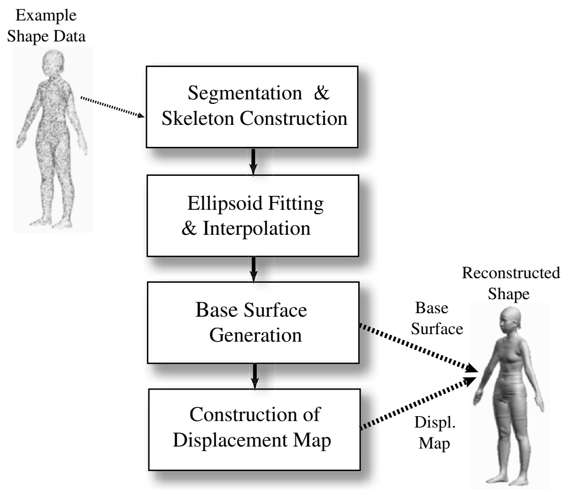

Figure 1: Overview of our modeling scheme.

2. *Ellipsoid fitting and interpolation*
Each arm or leg is partitioned into several subvolumes along the skeleton; and each volume is approximated by a key ellipsoid that fits tightly within its interior.

3. *Base surface as a generalized cylinder*
A base surface for the skin layer is constructed as the envelope of an ellipsoid that sweeps through the key ellipsoids. To simplify the computation, we approximate this sweep surface by the sweep of a cross-sectional ellipse of the moving ellipsoid. The base surface is then generated as a generalized cylinder that is connected to an ellipsoid (at a joint), and thus to another generalized cylinder.

4. *Construction of displacement map*
The fine details of the skin layer can be recovered using a scalar displacement function that relates the base surface to the original surface. The displacement function is represented using a multilevel B-spline approximation [14].

5. *Deformation of arms and legs*
We can bend arms and legs represented in this way quite simply by bending their skeletons: the key ellipsoids and the sweep surfaces follow. The ellipsoid at a joint must accommodate a wide range of angles; moreover, the corresponding cross-sectional planes must rotate about the axis of a joint. The overall shape of arms and legs can be changed by controlling the size of a moving ellipsoid.

4 Reconstruction Process

In this section, we explain our scheme for representing a human body in a simple layered structure.

4.1 Skeleton Construction

We segment the input data of a human body or a virtual character into arms, legs, and torso as shown in Figure 2. Crotch point, armpit points, and shoulder points are detected based on their geometric definitions. Alternatively these feature points can be manually specified or modified by the user. Data points for each body part are arranged so that they form cross-sections along the skeleton.

The skeleton of each leg is constructed by connecting points corresponding to joints such as the ankle, knee, and hip; these locations can be obtained from geometric or statistical criteria [11]. The skeleton of an arm is determined by wrist, elbow, and shoulder points in a similar way. Figure 2 shows how simple skeletons are constructed.

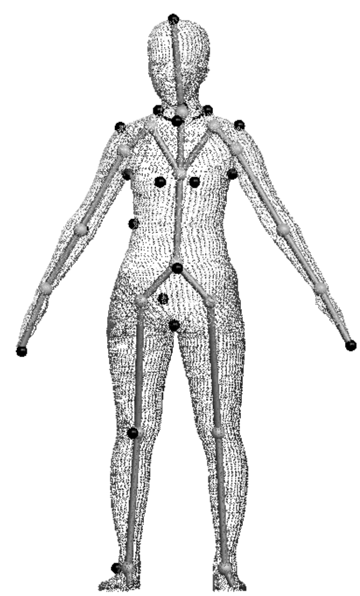

Figure 2: Segmented human body and skeletons; estimated feature points are marked with solid balls.

4.2 Fitting Key Ellipsoids

Next, the interior volume of an arm or a leg is approximated by a sequence of key ellipsoids. For this pur-

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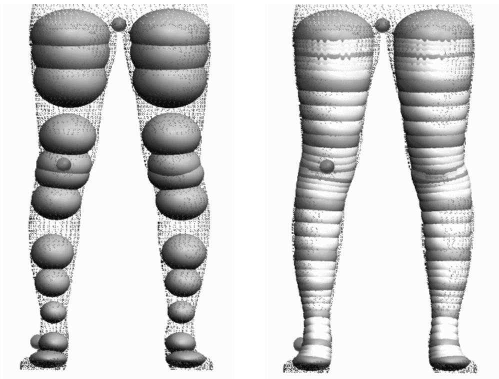


(a) **(b)**

Figure 3: Interpolation of ellipsoids to fit a limb: (a) Key ellipsoids, and (b) intermediate ellipsoids generated by interpolation.

pose, we partition the data points into disjoint subvolumes along the skeleton and fit an ellipsoid into each volume. By interpolating these key ellipsoids, we generate a smooth motion of an ellipsoid. The swept volume of the moving ellipsoid approximates the interior volume of the arm or leg.

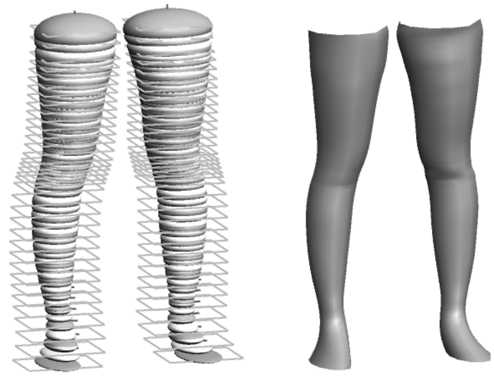
Fitting an optimal ellipsoid into an interior volume is computationally rather expensive [3, 23]. Therefore we simplify the fitting procedure by considering ellipsoids with their major axes parallel to the coordinate axes. Figure 3(a) shows the result of fitting these simple ellipsoids into the legs of a human body. Although the ellipsoids have a fixed orientation, Figure 3(b) shows that their swept volume tightly approximates the interior volume of each leg.

4.3 Smooth Interpolation of Ellipsoids

Once several key ellipsoids have been generated along a skeleton, we generate a smooth sequence of intermediate ellipsoids by interpolating the key ellipsoids. Since we only allow ellipsoids to be translated and scaled, this only requires smooth interpolation of the center positions and scale factors, which is considerably easier than the interpolation of general affine motions [10]. Figure 3(b) shows a typical example.

4.4 Base Surface Generation

Even if the swept volume of the moving ellipsoid tightly approximates the interior volume of an arm or leg, it is not easy to compute its exact envelope



(a) (b)

Figure 4: Approximation of the envelope surface of a leg: (a) Key ellipsoids and cross-sectional planes along the sweep trajectory curve, (b) sweep surface generated by the moving ellipse.

surface. In general, this is a high-degree non-rational algebraic surface; and its generation requires computing the zero-set of a trivariate equation [8, 13]. To make things simpler, we approximate the envelope by the sweep surface of a moving ellipse. This yields a sweep surface that is completely contained in the exact envelope surface, but we found that this approximation works very well in our application.

Figure 4 shows how an envelope surface can be approximated using the sweep surface of a moving ellipse. The upper and lower parts of the legs shown in this figure were constructed as sweep surfaces and connected by a knee approximated by an ellipsoid. The moving ellipse is a cross-section of the moving ellipsoid that shares the ellipsoid's center and lies in a plane parallel to the xy-plane. In this form, the sweep surface can be parameterized in a straightforward manner. The sweep surfaces and the ellipsoid at the knee form a base surface that provides a parametric domain for representing the detailed shape of each leg.

4.5 Construction of the Displacement Map

Fine details of the original shape are represented using a map of displacements from the base surface. The base surface consists of a cross-sectional ellipse moving along the skeleton, and the data points on the original surface follow the same sequence. Thus it is easy to measure the distance from an ellipse to the detailed surface, because the latter is represented by data points that lie on the corresponding

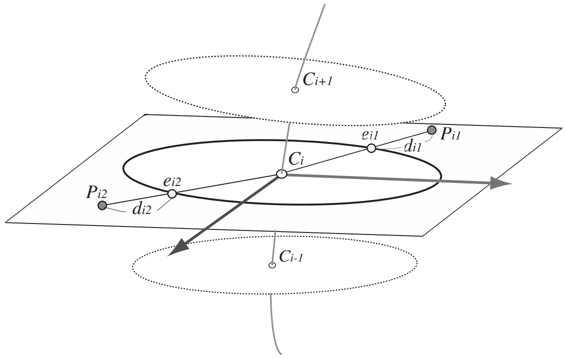


Figure 5: Sampling of scalar displacement values on a cross-sectional ellipse.

cross-sectional plane. (This approach is simpler than that of taking signed distances along the surface normals [16].)

Individual displacements may be measured by shooting a ray from the center of an ellipse to a data point and intersecting the ray with the ellipse; alternatively we can shoot a ray from the center to a point on the ellipse and intersect the ray with the polygon formed by the original data points on that cross-sectional plane. In either case, given an ellipse C_i, a point $\mathbf{e}_{ij}$ on the ellipse, and the corresponding data point $\mathbf{p}_{ij}$ (see Figure 5), the distance between $\mathbf{p}_{ij}$ and $\mathbf{e}_{ij}$is measured as a discrete bivariate function:

$$D(u_{ij}, v_i) = d_{ij} = \|\mathbf{p}_{ij} - \mathbf{e}_{ij}\|, \\ i = 1, \ldots, M, \quad j = 1, \ldots, N_i,$$

where (u_{ij}, v_i) is the surface parameter for the point $\mathbf{e}_{ij}$ on the sweep surface of C_i, M is the number of cross-sections, and N_i is the number of data points on the cross-section.

A smooth displacement map can be obtained by interpolating the sampled discrete displacement values. Instead of using a global approach, we employ the multilevel B-spline approximation proposed by Lee et al. [14], which is computationally efficient and also provides a hierarchical construction for the displacement map. Using this method, one can generate a hierarchy of C^2-continuous B-spline functions that approximate the given data values; and it is also faster than other scattered-data interpolation techniques [14]. Another important advantage is that it allows multi-resolution editing of the displacement map [15].

In multilevel B-spline approximation, the quality of approximation is controlled by the size of the control lattices: the finest control lattice must be very dense for a good approximation. We use an adaptive control lattice hierarchy and adjust the size of the finest control lattice to correspond to the sampling interval.

Figure 6 shows arms and legs reconstructed using the displacement map.

4.6 Deformation

Once the arms and legs have been represented in a layered structure, their shapes can be deformed in various different ways, either by changing the trajectory of the moving ellipsoid or by scaling its size, uniformly or non-uniformly. Figure 7 shows the results of scaling the size of moving ellipsoids. Figures 7(b) and 7(c) show uniform scaling and Figure 7(d) shows non-uniform scaling of the moving ellipsoid.

The bending of arms and legs can be realized simply by articulating their skeletons: the moving ellipsoid will change its trajectory to follow the skeleton. The ellipsoid at a joint must accommodate a wide range of angles; moreover, the corresponding cross-sectional planes must rotate about the axis of a joint. A simple way of handling this problem is by sampling the ellipsoids, and their corresponding cross-sectional ellipses, more densely when the angle gets more acute. Figure 8 demonstrate the effect of bending a leg.

On the other hand, the twisting of arms and legs can easily be implemented by smoothly changing of the orientation of the moving ellipse about its center.

5 Experimental Results

To illustrate the situation where data is only obtainable for a single pose, , we consider the modeling and deformation of the Stanford Armadillo, a virtual character with a human-like articulated body with arms and legs. Our modeling and deformation technique can nevertheless generate the Armadillo in many different poses, as shown in Figure 10.

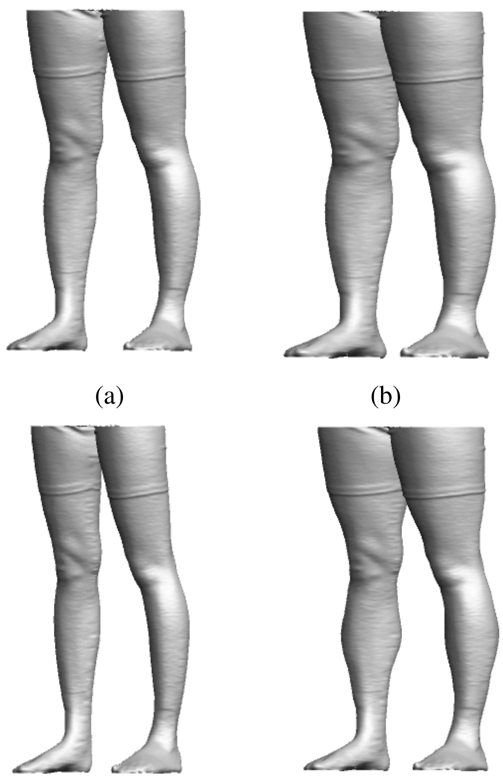
Even when using range scanning and a human subject, some attitudes, such as running or jumping, are extremely difficult to acquire. Using our approach, it was relatively easy to produce the poses shown in Figure 11

6 Conclusion

We have presented a new approach for modeling arms and legs from data corresponding to a single

(a) (b)

Figure 6: Reconstruction of arms and legs: (a) Base surfaces of legs (left) and displaced surfaces (right), and (b) base surface of an arm (left) and displaced surface (right).



(a) (b) (c) (d)

Figure 7: Results of scaling: (a) the original shape; (b) 120% fatter, (c) 80% thinner, and (d) 'muscular' legs by achieved by differential scaling.

pose or given as a static point set or polygonal model. These articulated body parts are reconstructed into a layered structure using skeletons, key ellipsoids, sweep surfaces, and displacement maps. An ellipsoid with a fixed orientation moves along the skeleton and generates the sweep surface; this is then approximated by a moving ellipse, which is a cross-section of the moving ellipsoid. These assumptions greatly simplify the computation of sweep surfaces.

The theory behind our approach is based on various mathematical results from previous work. Our algorithm has been presented in an informal style so that the basic idea can easily be understood by a general readership. Nevertheless, there are many challenging mathematical problems related to this approach. For instance, in bending the skeletons of arms and legs, their base or detailed surfaces may self-intersect. Fortunately, this usually occurs in places that are invisible from common viewpoints; but, in some applications, these self-intersections may cause computational problems. Future work will address issues of this sort.

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Figure 8: Results of bending a leg: Moving ellipsoids of a leg are also shown at two extreme poses (extreme left and bottom right).

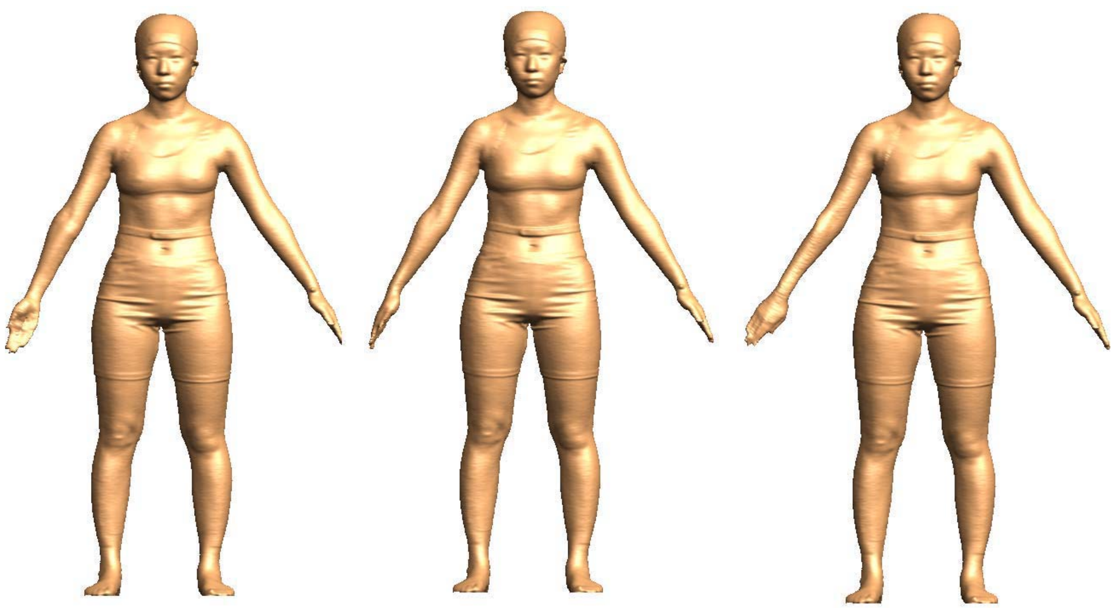

Figure 9: Result of twisting an arm.

Figure 10: The Stanford Armadillo in various different poses: each pose is generated by mapping the joint angles on to the leg skeletons.

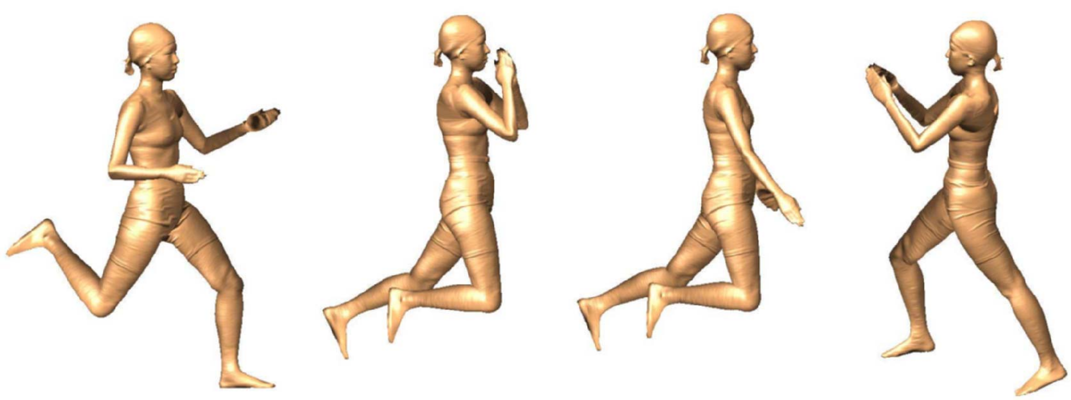

Figure 11: A woman athlete in various poses: each figure is generated by articulating the skeletons of her arms and legs.

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