Recent Developments in Skin Deformation for Character Animation

Shaojun Bian, Lihua You and Jian J. Zhang
National Centre for Computer Animation, Bournemouth University, Bournemouth, U.K.

Keywords: Skin Deformations, Geometric Techniques, Physics-based Techniques, Data-Driven Methods.

Abstract: Achieving realistic skin deformation efficiently is a very important task for character animation. With the development of skin deformation, the efficiency and effectiveness of character modelling and animation have been obviously enhanced. In this paper, we survey the recent literature on skin deformation according to three types of approaches: purely geometric, physics-based, and data driven. Especially we focus on the work since 2009. We review the problems they primarily tackles, the methodologies they applies, and the advantages and disadvantages they have. At last, we discuss directions for future research.

1 INTRODUCTION

Achieving realistic skin deformation efficiently is a very important task for character animation. In order to create high-quality character models, lots of skinning deformation algorithms have been developed. These techniques could be roughly classified into three categories: purely geometric techniques, physics-based techniques and data-driven techniques.

Purely geometric techniques focus on geometric operations of changing the geometry of character models instead of underlying physics of skin deformations. This type of methods are good at performances in calculating deformed skin models, but less realistic.

Physics-based methods consider the underlying physics of skin deformation and materials attributes. This kind of methods could produce more realistic skin deformed shapes but commonly need high computing cost.

Data-driven methods generate new skin deformations through example character skin models, without considering any underlying physics. This category of methods could create highly realistic skin deformations. The vital problem is how to reduce input character example models but still achieve high realistic results.

This paper focuses on recent developments in skin deformation methods, especially those since 2009. The paper is organized as follows. According to the three general categories of skin deformation methods, purely geometric techniques are reviewed in Section 2. Physics-based techniques are investigated in Section 3. Data-driven methods are examined in Sections 4. Finally, conclusions and future work are discussed in Section 5.

2 GEOMETRIC TECHNIQUES

Due to the exiting problems of unrealistic deformation created by geometric based methods, such as the collapsing-joint, candy-wrapper, bulging-joint and distorted normal, more explorations have been launched. In this section, we mainly illustrate five influential algorithms, which could effectively improve skin deformation shapes generated geometrically.

2.1 Implicit Skinning with Contact Modelling

As traditional geometric-based skinning techniques, linear blending skinning(LBS) (Magnenat-Thalmann, 1988) or dual-quaternion skinning(DQS) (Kavan, 2008) are good at performances, which could meet the need of industry, but the deformations generated are less realistic, because of the collapsing-joint and candy-wrapper (Magnenat-Thalmann, 1988) and bulging joint and distorted normal (Kavan, 2008).

Implicit skinning with contact modeling is one purely geometric method, which could effectively address skin contact artifacts at joints and muscular

Bian S., You L. and Zhang J..
Recent Developments in Skin Deformation for Character Animation.
DOI: 10.5220/0005272001220129
In *Proceedings of the 10th International Conference on Computer Graphics Theory and Applications* (GRAPP-2015), pages 122-129
ISBN: 978-989-758-087-1

bulges in real-time without using time-consuming collision detection (Vaillant, 2013).

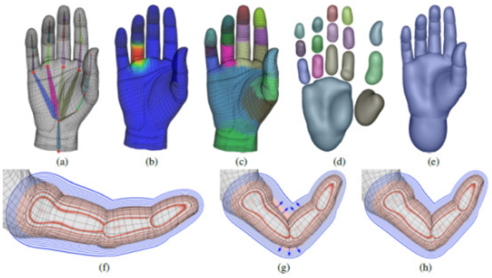


Figure 1: Overview of implicit skinning with contact modelling (Vaillant, 2013).

An overview of implicit skinning with contact modeling is demonstrated in Figure (1) by Vaillant et al. in (Vaillant, 2013). This method uses the initial settings shown in Figure 1, i. e., a mesh equipped with an animation skeleton (Figure 1a), the associated weights (Figure 1b) calculated with the heat diffusion technique , and mesh segmentation (Figure 1c) with respect to skeleton bones.

Then, each part of the mesh is approximated with implicit surfaces computed as 0.5-isosurfaces of Hermite Radial Basis Functions (HRBFs) (Wedland, 2005, Maceˆedo, 2011) Figure 1 (d) through a smooth scalar field f_i. After these steps, each vertex v of the mesh stores its current field value f_i containing the detailed information. Next, a single field function f is defined from the combination of the$f_i$using either the union (Ricci, 1973), gradient-controlled blending or gradient-controlled bulge operators (Gourmel, 2013), depending on the desired result (Figures 1(e,f)). Following that, underlying field functions f_i and object rigid transformations are utilized to get the deformed mesh. The values of mesh vertices are iterated through the gradient of f (Figure 1(g)) until they meet the original values or represent a contact surface. By doing so, the needed object deformation is created (Figure 1(h)).

The merits of this method include maintaining the character volume after deformation, generating contact shapes and bulging near joint without any optimization and collision, so that the computing time could be saved.

The demerit of this method is that the deformed shape quality depends on the option of the initial geometric skinning method. When the method could avoid deep self-intersections, the results will be of high-quality.

2.2 Bulging-Free Dual Quaternion Skinning

This bulging free dual quaternion skinning method (Kim, 2014) also considers both the shortage of LBS in collapsing-joint and candy-wrapper effects, and the problems of DQS in bulging joint and distorted normal.

In order to tackle the above mentioned skinning shortage, the first step, is to concern on correcting the positions of vertex. It pre-computes every vertex distance in the rest pose. When the vertex is in the bone-zone, the distance means to the bone. While the vertex in the joint-zone, the distance is to the joint. Then, use the run-time algorithm to correct vertex positions, pushing the red curve toward the corresponding bone or joint.

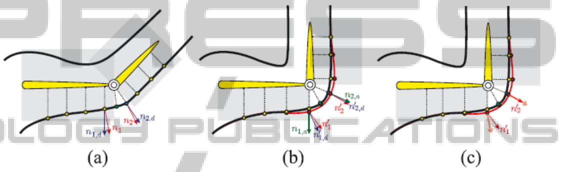


Figure 2: Overview of normals correcting (Kim, 2014).

The second step is to correct the distorted-normals shown as Figure (2). Firstly, give every vertex a vector for reference (blue). Then after deformation, another reference vector $n'_{i.a}$ (green) is rotated from $n'_{i.d}$ (blue) by a transform for every vertex. Finally, use the transform onto n'_{i}(thin red), the thick red vector could be calculated, so that the distorted normal is corrected. Some unnatural shading of the deformed skin could be eliminated.

This method mainly uses two procedures to solve the bulging joint and distorted problems of DQS. It is simple and easy to implement but the normal correction algorithm still faces computation overhead problem.

2.3 Stretchable and Twistable Bones Skinning

Stretchable and Twistable Bones for Skeletal Shape Deformation approach (STBS) (Jacobson, 2011) makes some modifications on the current popular method, skeleton-based linear blend skinning (LBS), to tackle the problems on elbow-collapse and candy-wrapper effects.

This approach could keep the original model skeleton rig and bone weights after stretching and twisting deformation, and still maintains a good performance.

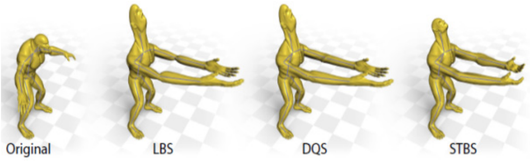


Figure 3: Results comparison of STBS with standard methods (Jacobson, 2011).

As shown in Figure (3), there is a beast rest pose model with its skeleton. By using LBS, the user stretches the neck, and twists and stretches the arm. It's obvious that the head and hand got an explosion; the joint also appears candy-wrapper. Then DQS is used. The arm twists correctly, but the stretched artefact is still apparent. Finally, the results of proposed method STBS shows correct twisting and no explosions when stretching, due to one extra set of weights per bone.

The core of STBS is one extra scalar weight function per bone. This function could be generated by manual operation or automatic computer calculations. One approach to define the extra weights for joint points is to use inverse Euclidean distance weighting shown by Equation (1),

$$\mathrm{j}_{\mathrm{IEDW}_\mathrm{i}}(\mathrm{p}) = \frac{1}{\mathrm{d}_\mathrm{i}(\mathrm{p})^\alpha} \tag{1}$$

Where $\mathrm{d}_\mathrm{i}(\mathrm{p})$ is the Euclidean distance from joint p to i on the rest position.

STBS aims to expand the possible space of deformation simply, allow stretching without explosion and smooth twisting but it cannot avoid self-collision artefact.

2.4 Differential Blending Deformation

Creating a realistic character model and generating the diverse poses of the model in computer is increasingly difficult and time-consuming, generally because of two reasons. One is the character rig system may limit the space of achievable poses, and the other is that manipulating a character rig system to obtain desirable poses requires huge manual work, due to lots of the rigging parameters.

The Differential Blending approach (Cengiz Öztireli, 2013) introduced here, deals with the above mentioned shortages of skeletal deformation by using the 2D hand-drawn animation as a guide (Blair, 1994).

The core of this novel blending method stays in blending skeletal large and disparate transformations into small ones. Firstly, represent all transformations differentially. Then, calculate the averages of these transformations. Finally, obtain the desirable blended transformations between animation key-frames with much lower time and labour cost. The user draws a stroke to select a bone. Then transformations from the frames on the drawn curve to the select bone are computed to get the final deformed model, shown in Figure (4).

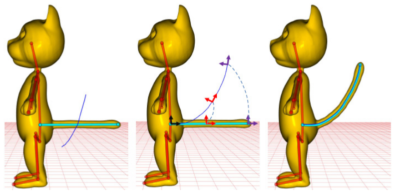


Figure 4: The process of skeletal deformation via sketching by 2D concepts (Cengiz Öztireli, 2013).

This method takes references from traditional 2D illustration, to expand the possible poses space, and could generate models that are difficult by current 3D deformation methods.

2.5 Delta Mush Model

During computer animation, how to define the efficient rig without undesirable deformation is a vital problem should be tackled. If the rig is constructed inefficiently, it will waste much time and labour cost.

Delta Mush (Mancemicz, 2014) is a Voodoo deformer, which could smooth arbitrary deformation of a polygonal mesh and also preserve the valuable original detail of the character model. "Delta" means the changes of original models; "Mush" means the smooth operation.

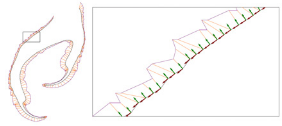


Figure 5: Overview of Delta Mush algorithm (Mancemicz, 2014).

As shown by Figure (5), the smoothed mesh (black) is created by "mushed" in cross-section. The smoothed mesh, the tangent (red) and the normal (green) compose the local coordinate system. Then a vector offset (orange) of every initial mesh vertex is calculated in the local coordinate space, called "delta" here. Next, the smoothed mesh is transformed according to the orange offset to create the final deformed mesh (purple) (Mancemicz, 2014).

Standard geometric smoothing techniques based on discrete Laplacians (Botsch, 2010) unavoidably lose both the geometry details and the volume on convex surfaces. The Delta Mush deformer, as a low-pass filter, focuses on the geometry deformation instead of geometry itself (Mancemicz, 2014), could just decrease these losses of model details and volume.

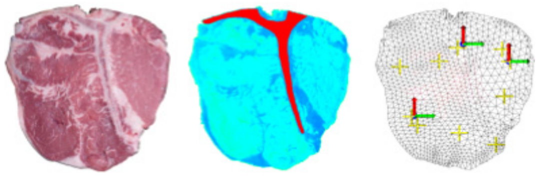
3 PHYSICS-BASED TECHNIQUES

Physics-based techniques play a very important role in computer modelling and animation currently. This kind of methods could produce more realistic skin deformed shapes but commonly need high computing cost. In this section, we mainly review four physics algorithms which fairly solve the tough tasks on deformation of complex heterogeneous objects and soft materials.

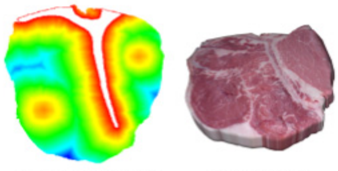
3.1 Sparse Meshless Model

Physics-based methods consider the physics principles of skin and the material attributes. Because of the complex heterogeneous material of real objects, common methods often regard it into one homogeneous material for modelling. Once taking use of current method for modelling the complex heterogeneous objects realistically, it needs to deal with lots of varying material parameters which seems unfeasible previously.

The Sparse Meshless model (Faure, 2011) of complex deformable solids deals with above questions using various stiffnesses to simulate complex heterogeneous objects. By maintaining the frame-based meshless framework introduced in (Gilles, 2011), this method obtains the physical realism of character animation by using skeleton subspace deformation (SSD) on character volume and continuum mechanics.



(a) T-Bone Steak (b) Stiffness (c) Discretization



(d) Compliance distance (e) Deformation

Figure 6: Overview of Sparse Meshless model (Faure, 2011).

The T-bone steak depicted in Figure 6(a) is composed by complex heterogeneous materials, the rigid bone, muscle and fat. Figure 6(b) is the volume stiffness map of it. As Figure 6(c) reveals, the proposed method could simulate it by only three moving frames and ten integrating points. And user creates the placement of frame by a new compliance-scaled distance Figure 6(d). The deformed result could be seen in Figure 6(e). When one force is projected on right, the meat rigid structure is preserved and the other different material also moved correspondingly.

Compared with previous approaches, this model adapts coarse deformation functions to efficiently simulate objects of complex heterogeneous material at a high performance and less control nodes but the accuracy should be improved.

3.2 Efficient Elasticity Technique

As for the high computational cost of physically based approach to generate the life-like human and animal models, geometric or data-driven skinning approaches are always used. But in that case, the pinch-free geometry could not be preserved. Therefore, some previous works have been done to simplify the physical simulation. The principle component analysis of off-line elasticity simulation (Kry, 2002) is use to enhance the interaction of physics-based SSD.

The novel elasticity model introduced in (McAdams, 2011) focuses on solving the soft tissue deformation problems. It innovatively discretizes co-rotational elasticity over a hexahedral lattice to diminish the self-collision artifacts and maintains soft-constraints for character realism.

Figure 7: Overview of the efficient elasticity model (McAdams, 2011).

As shown in Figure 7, there's a character mesh and its skeleton (left). Then a corresponding hexahedral lattice is defined (middle). The original mesh is deformed by the rules of self-collision and volumetric elasticity.

Taking a reference on (Chao, 2010), this corotational elasticity discretization method accurately treats the force into derivatives to get a more robust solver than the simplified warped-stiffness approaches with little manual cost.

3.3 Skeleton and Skin Coupled Physics Framework

Recently some outcomes promote the controlling of human-like rigid characters (Yin, 2007, Coros, 2010) and highly dynamic motions (Liu, 2012, Brown, 2013). But sometimes the motions of character skin and soft body always influence the dynamic of skeleton. In the long run, biomechanical algorithms that truly simulate human anatomy are exactly necessary to avoid the problem (Lee, 2009), unfortunately still need high computing cost.

Here, this physically based framework for simulating and controlling life-like soft material characters could couples the dynamics of skeleton and soft body (Liu, 2013). In detail, this simulation and control system works as shown in Figure 9:

(1) Take the character skeleton and surface mesh as input data.

(2) In order to couple the skeleton dynamic and skin geometry, user should construct one coarse volumetric mesh with a reference configuration X. More exactly, one soft body dynamics solver is obtained to construct the volumetric mesh. And a rigid body dynamics solver is obtained to simulate the character skeleton.

By coupling the dynamics of skeleton and skin, this physics-based framework shows good performance on character large deformation and joint effects.

3.4 Embedded Thin Shells Wrinkle Deformation

Wrinkles simulation takes a very important part in object deformation. When the material properties of the surface and underlying volume change, wrinkles will happen, causing by a force. The wrinkle appearances commonly occur on human skin (Danielson, 1973), but also could appear at other kinds of objects, like fruits and mountain (Genzer, 2006).

The embedded thin shells framework showed in (Remillard, 2013) could highly simulate complex object with a soft interior and a harder skin. The core of it is to combine high resolution thin shells with coarse finite element lattices and confirm frequency based constraints. And it could generate the predicted wrinkle by calculating the physical parameters of characters.

This method also adapts one novel two-way coupled model to eliminate the computational cost of internal volumetric elements (Remillard, 2013). To elaborate, this technique has the following phases:

(1) Taking use of the embedded mesh method and replaces the embedded mesh with a thin shell, combining both systems just with position constraints.

(2) Considering the constraints. They should be non-intervention with wrinkle formation or large character deformation.

(3) C1 quadratic shape functions to represent the interior deformations, achieving seamless effect on discretization boundaries.

This solver produces static solutions for the shell. These shells are thin enough and cannot cause visual dynamics. The high-resolution deformation of these shells could be used to contribute forcing on the low-resolution interior dynamics (Remillard, 2013). Thus, the process could largely eliminate the cost of deforming the interior of objects.

4 DATA-DRIVEN METHODS

Data-driven methods generate new skin deformations through example character skin models, without considering any underlying physics. Once example models are sufficient, this category of methods could create highly realistic skin deformations. Here, we describe four data-driven algorithms developed for decreasing the input character example data but still could accomplish high realistic results.

4.1 Smooth Skinning Decomposition

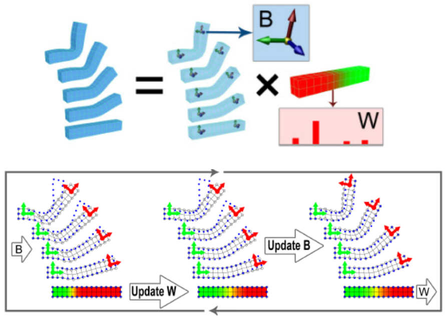


Figure 8: Overview of this skinning decomposition method. B means rigid bone transformations and W means a sparse, convex bone-vertex weight map W (Le, 2012).

Smooth Skinning Decomposition with Rigid Bones (SSDR), is one effective approach that automatically extract linear blend skinning (LBS) from input example models. As shown in Figure 11, a set of example models are decomposed into bone transformations and a sparse, convex bone-vertex weight map. Only these little rigid bones and the weight map are used to simulate the skin deformations of character models by SSDR (Le, 2012). More specifically, this skinning decomposition is solved as one constrained optimization problem. The summation of squared error of vertices on models deformed using LBS has to be least. Shown as follows:

$$\min_{w,R,T} E = \min_{w,R,T} \sum_{t=1}^{|t|} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} \left(R_j^t p_i + T_j^t \right) \right\|^2 \quad (2)$$

Where $\mathrm{w_{ij}}$ is the influence of bone j to vertex i, $\mathrm{p_i}$ is the coordinates of vertex i at the rest pose, |B| means bones' number, and $\mathrm{R_j^t}$ and $\mathrm{T_j^t}$are bone j 's rotation and translation matrix on t stage.

The skinning methods in (James, 2005) and (Hasler, 2010) make a novel treatment called soft constraints which are the constraint of bone orthogonal transformation and bone-vertex convex weight map. But this SSDR technique treats these constraints as hard constraints to avoid the collision between totally satisfying the constraints and minimizing the reconstructing error. By employing the SSDR model, the bone transformation could be obtained simply and the deformed shapes are accurate but it needs high computational cost.

4.2 Enriching Coarse Interactive Deformation

Simulating elastic object is really necessary in character modeling area. Many efficient approximate deformation method have been developed, but they always cannot do good on simulating complex geometric models with nonlinear materials and dissatisfied computing cost.

Considering on the aforementioned problems, the enriching coarse method follows the idea that, the non-linearly deformation of geometric object could be decomposed as a superposition of an approximate model and displacements on deviation between approximate model and real geometric model (Zhong, 2005). It proposes one efficient dynamic interactive coarse model coupled with enriching details form a high-resolution quasi-static model in a data-driven way (Seiler, 2012).

The first stage of this algorithm is the pre-computation. During this stage, there's an interactive tool which could be used to act on the object and create object deformation. The aforementioned procedure acts again but with higher resolution quasi-static simulation. After every example interaction, the difference between the two models is calculated as a displacement field for next time's use, called stamp in this method.

The second stage of this algorithm is to obtain the approximated character deformation model by coarse simulating. And weight (w) is extracted to blend the stamps using non-linear correlation. Then according to the coarse model of object and the blended stamp, the high resolution model with enriching details could be produced (Seiler, 2012).

This approach proposes the stamping way to enhance the quality of interpolation for simulating elastic object with details. But the usage direction on dynamic deformation should still be exploded.

4.3 Sparse Localized Components Deformation

This Sparse Localized deformation method decomposes a whole model deformation into some sparse and spatially localized modes through an animated sequence (Neumann, 2013).

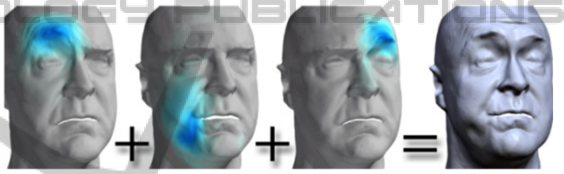


Figure 9: decomposed sparse and local deformations (blue) could be added to create a new deformation needed (Neumann, 2013).

As shown in Figure 9, summing several deformations of localized components produces one new facial expression. Separate motion effects have been produced automatically, like eyebrow showed in the figure.

Firstly, a sparsity-inducing regularizer is edited for mesh deformation setting. Then design one mechanism to automatically decompose sparse and localized mesh components efficiently which could be guided by input data from user. Besides, one effective decomposition optimization way has also been developed.

Based on the important theories on matrix decomposition such as Non-Negative Matrix Factorization (NMF) (Lee, 2000), Robust PCA (Candes, 2011), and Sparse PCA (Zou, 2006), this new efficient data-driven algorithm could decompose mesh sequence into sparse deformation components without considering the real underlying physical movements.

The sparse localized decomposition method highly deals with some tough mesh processing and editing tasks, such as animation editing on faces, body, cloth and statistical geometry processing.

4.4 Non-Linear Heterogeneous Soft Tissue Deformation

Recently, the methods on simulating soft object deformation have been developed to solve the heterogeneous materials problem. But it exactly is still a time-consuming work and another tough problem is material nonlinearities.

This data-driven method proposes one novel way to simulate the deformations of non-linear heterogeneous soft object. Finite element methods and a range of measured example objects deformation have been used, saving lots cost of choosing material parameters (Bickel, 2009). As always, a four stage process applies:

(1) Every measured example deformation of objects is transformed into a local element-wise strain space.

(2) Model the stress-strain relation of material deformation into locally linear sample.

(3) Through radial basis functions (RBFs) (Buhmann, 2003), interpolate and simulate the non-linear deformation of material in strain space.

(4) Finally, by using an easy-to-implement elastostatic finite-element solution of the non-linear material examples based on incremental loading, the accurate soft object deformation models could be generated on lower computation cost (Bickel, 2009).

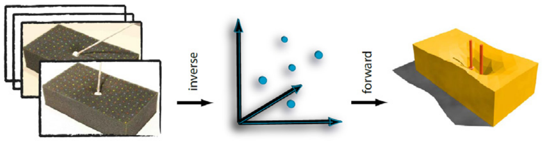


Figure 10: Overview of this novel method on representing the soft tissue deformation (Bickel, 2009).

As shown in Figure 10, put a force on different positions of the object, user could get a set of example deformations. And the direction and magnitude of forces used should be stored and processed. Based on the abovementioned deformation and force, users estimate its stress-strain relationship and create a space composed with these samples. After that, when a new force is set, the deformation needed could be interpolated by RBFs on the basis of these examples in strain space.

The major advantage of this method is the capability to generate new deformation of complex heterogeneous soft object simply, regardless of tough material parameters setting. But this method only processes the force on the probes' shaft direction. To be realistic, the tangential forces and frictions should also be considered in future work.

5 CONCLUSIONS

In this paper, we mainly make a survey upon the latest developments of skin deformation techniques, especially since the year of 2009. According to the review and comparisons on these latest and contributable methods, we have known that the unrealistic problems of geometric-based deformation have been greatly tackled while still maintaining good performances. The difficulties of physics-based techniques, such as deformation of complex heterogeneous objects and soft materials, have been addressed to avoid high computing cost. Besides, the vital need of reducing input example models on data-driven algorithm has also been substantially processed. Every approach has their own merits, their intrinsic attributes still appears some demerits accordingly.

Thus, it's still necessary to develop more effective combination operations which could remedy the shortages of each kind of methods; highly maintain the character details during deforming and avoid unnecessary calculations.

The first possible combination operation may be a hybrid technique which combines the deformation mechanics of skin surfaces with data-driven approaches to reduce example skin shapes and achieve good realism.

The second possible combination operation is to first transform skin surface models into a wireframe representation, and introduce deformation mechanics of wires and data-driven approaches to create realistic skin deformations efficiently.

ACKNOWLEDGEMENTS

This research is supported by the grant of 2013 International Exchanges Scheme (Grant no. IE131367), the Royal Society, United Kingdom.

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