

Basic theory behind (X)PBD

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1 Introduction

1.1 What is (X)PBD?

PBD is one of the simulation theories that basically simulates [soft-body](#) or [elastic-body](#).

PBD (Position Based Dynamics) proposed at [4] is a popular method because of its stability and ease of implementation. The reason for them is the same, PBD computes physical simulation only using positions inside the [Iterations](#) and all we have to do is compute displacement and modify them. In other words, we don't have to use complicated numerical analysis theories, it sounds pretty good.

But, in contrast to ease of implementation, it isn't easy to understand PBD's background theory. This is the problem when modifying PBD depending on your purpose.

If you start your research from the original PBD paper[4], you will wonder how the authors derive constraints' formulations or why this solver works well. Or you start from XPBD [7], you will be confused by the suddenly appeared Lagrange multiplier or energy potential that we don't know how to handle. Unfortunately, we can't know much from them and it may be common in literature search, there is no clear path to learning them. Then, I decided to write a guidebook on the underlying theory of PBD.

1.2 Difference from existing PBD coursenote

Actually, there are some course notes on PBD written by authors who published papers on PBD and XPBD, e.g. [13]. These course notes describe the basic style of PBD and its extensions. But there is the same problem we saw in [4] and [7], that is, how to implement is described but why this method works well is not. Thus, I believe that this document isn't meaningless. Well then, let's start the journey to XPBD!

1.3 Learning Path

2 The history of PBD

I think starting from history is a good way to learn something because there are no leaps in logic and it will be easy to understand where we are. However, there is certainly redundancy, so you can skip this section to save time. I'll make an effort to write that you can understand everything even if you skipped this section.

The history of PBD can be roughly divided into three parts. Let them be pre-PBD, post-PBD and post-XPBD.

2.1 Pre-PBD

The flow of the pre-PBD began from the appearance of constraint dynamics([14], [15] and [16]) through "*Large Steps in Cloth Simulation*"[1] used [constraints](#) as shape representation and simulates cloth with energy form [constraints'](#) gradients, "*Advanced Character Physics*"[2] introduces position-based approach derived from Verlet's integration scheme with the distance constraints and "*A Versatile and Robust Model for*

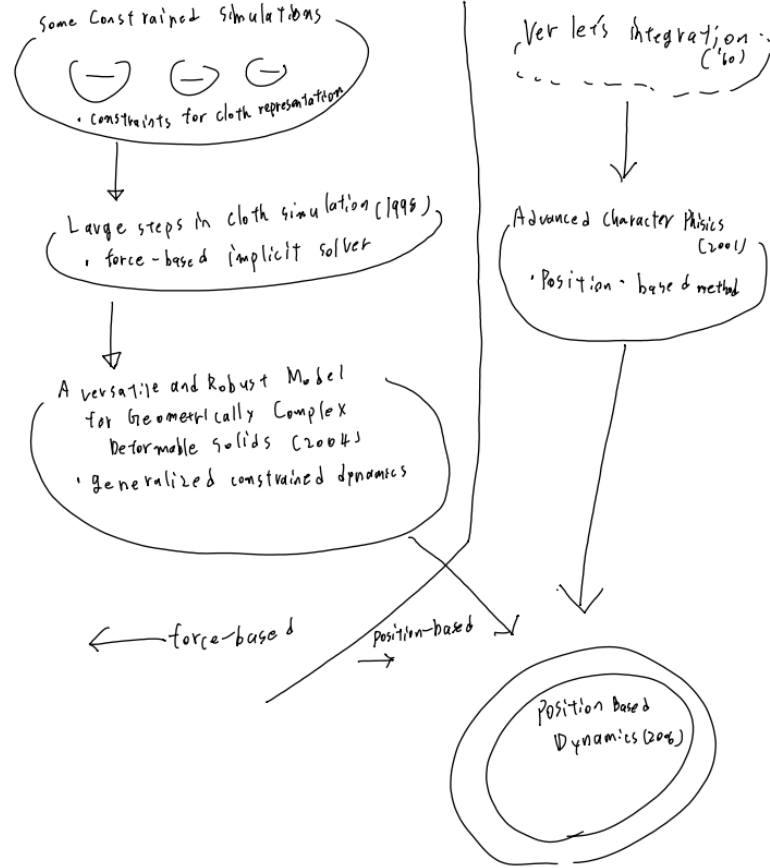


Fig. 1: history of pre-PBD

Geometrically Complex Deformable Solids [3] generalize [1]’s method. And, finally, *Position Based Dynamics* [4] introduced the generalized constraints method from [3] into [2]’s position-based simulation to use various constraints.

2.2 Post-PBD

From the published PBD paper, a lot of study about it has been done. The central development is resolving well-known PBD’s drawback whose result depends on [Iteration](#) times, at *XPBD: position-based simulation of compliant constrained dynamics* [7].

To understand XPBD, we need some knowledge of continuum mechanics. The theory directly used in XPBD is derived from *Interactive simulation of elastic deformable materials* [6] that uses the theory for [Lagrangian mechanics](#).

Besides that, some papers also influence XPBD, *Efficient simulation of inextensible cloth* [17] and *Strain Based Dynamics* [18] are examples of them. The former



Fig. 2: history of post-PBD

introduces the projection method described later. The latter invites physically based constraints to PBD.

Although there is relevance to XPBD, the key idea to construct XPBD is [6] and aren't the last two papers. In other words, to understand XPBD, we truly only have to read [6] or get the equivalent knowledge.

But, unfortunately, the key idea of XPBD provided by [6] doesn't have a sufficient explanation of where the authors get the formulation. Then, I guess a description later that seemed reasonable enough.

2.3 Post-XPBD

Shortly after published XPBD paper, a simple but important improvement was provided at "Small steps in physics simulation" [8].

!!!!In preparation!!!!

3 Physics

This section is devoted to fundamental physics.

Of course, the physics simulation field takes advantage of the basics. If we only handle trivial environments, classical mechanics can achieve simulation.

However, classical mechanics isn't enough to simulate complex objects or get plausible results. For example, Newtonian mechanics-based methods suffer from soft-body simulation and preserving the energies or the (angular) momenta. The algorithm of the soft-body simulation isn't trivial, and there is no definitive solution at present. Besides, artificial damping from unconservation that creates a gap between physical accuracy and the simulation result is also a matter. Therefore, a lot of methods are studied to solve them.

In this section, in addition to explaining classical mechanics, I also explain some physical theories that are used frequently in soft/elastic body simulation, Constrained dynamics, and Continuum mechanics.

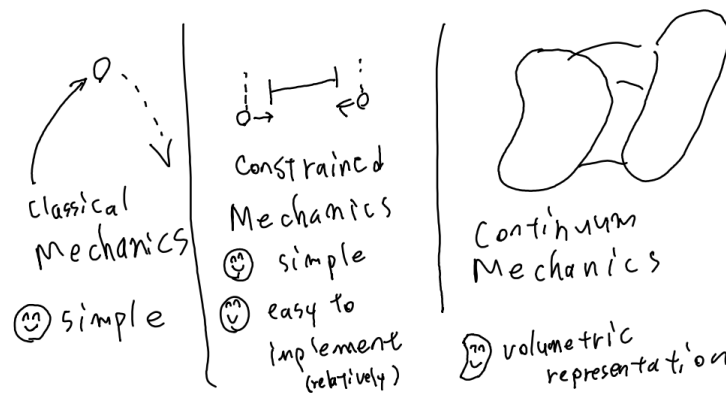


Fig. 3: Comparison of the physics

Although there are many other important theories, such as fluid mechanics or thermodynamics, I won't explain them because this document's subject is (X)PBD which focuses on soft/elastic body (actually, PBD can be used in fluid simulation...).

3.1 Classical mechanics

Let's start the physics course with classical mechanics.

First, please imagine a car running at a constant speed.

!!!!In preparation!!!!

3.2 Constrained Dynamics

!!!!In preparation!!!!

3.3 Continuum mechanics

!!!!In preparation!!!!

3.3.1 What is tensor?

!!!!In preparation!!!!

3.3.2 Force, strain, and stress

!!!!In preparation!!!!

3.3.3 Kirchhoff stress tensor

!!!!In preparation!!!!

3.3.4 Cauchy-Green deformation tensor

!!!!In preparation!!!!

3.3.5 St. Venant strain tensor

!!!!In preparation!!!!

4 Numerical integration

!!!!In preparation!!!!

4.1 The linear solvers

!!!!In preparation!!!!

4.2 Newton's method

!!!!In preparation!!!!

4.3 Iterative solvers

!!!!In preparation!!!!

4.4 What is the local/global solver

!!!!In preparation!!!!

4.5 Misc. topics

!!!!In preparation!!!!

4.5.1 Lagrange Multiplier

!!!!In preparation!!!!

4.5.2 LU decomposition

!!!!In preparation!!!!

4.5.3 Schur decomposition

!!!!In preparation!!!!

5 Numerical physics

!!!!In preparation!!!!

5.1 Verlet's integration

!!!!In preparation!!!!

5.2 Mass-spring system

!!!!In preparation!!!!

5.3 Explicit/implicit euler scheme

!!!!In preparation!!!!

5.4 Shape matching

!!!!In preparation!!!!

6 Column : In the terminology mess

!!!!In preparation!!!!

6.1 Newton*

!!!!In preparation!!!!

6.2 Euler*

!!!!In preparation!!!!

6.3 Jacobi*

!!!!In preparation!!!!

6.4 Lagrange*, Hamilton*, Hesse*

!!!!In preparation!!!!

7 Interpret the papers

!!!!In preparation!!!!

7.1 To PBD

!!!!In preparation!!!!

7.1.1 *Large steps in cloth simulation*[\[1\]](#)

!!!!In preparation!!!!

7.1.2 *Advanced Character Physics*[\[2\]](#)

!!!!In preparation!!!!

7.1.3 *A Versatile and Robust Model for Geometrically Complex Deformable Solids*[\[3\]](#)

!!!!In preparation!!!!

7.1.4 *Position Based Dynamics*[\[4\]](#)

!!!!In preparation!!!!

7.2 To XPBD

!!!!In preparation!!!!

7.2.1 *Geometric, Variational Integrators for Computer Animation*[\[5\]](#)

!!!!In preparation!!!!

7.2.2 *Interactive simulation of elastic deformable materials*[\[6\]](#)

!!!!In preparation!!!!

7.2.3 *XPBD : position-based simulation of compliant constrained dynamics*[\[7\]](#)

!!!!In preparation!!!!

7.2.4 *Small steps in physics simulation*[\[8\]](#)

!!!!In preparation!!!!

7.3 Bonus section : Projective Dynamics

!!!!In preparation!!!!

7.3.1 *Example-based elastic materials*[\[9\]](#)

!!!!In preparation!!!!

7.3.2 *Fast simulation of mass-spring systems*[\[10\]](#)

!!!!In preparation!!!!

7.3.3 *Projective Dynamics: Fusing Constraint Projections for Fast Simulation*[\[11\]](#)

!!!!In preparation!!!!

7.3.4 *ADMM \subseteq projective dynamics: fast simulation of general constitutive models*[\[12\]](#)

!!!!In preparation!!!!

7.4 **Post-XPBD**

!!!!In preparation!!!!

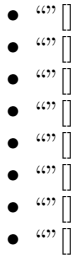
A Importance of papers

A lower number means more important. The papers' names are aligned in the lexicographic order as possible as I can.

1. You must read these papers if you want to understand (X)PBD. But if you want to understand them completely, I recommend reading the others also.
 - “*Position Based Dynamics*” [4] is one of the main subjects of this document.
 - “*XPBD : position-based simulation of compliant constrained dynamics*” [7] addressed a numerical artifact that makes dependency between stiffness and [Iteration](#) count or size of the time-step.
2. These papers are vital in understanding (X)PBD or have a strong impact on the field.
 - “*Advanced Character Physics*” [2] introduced position based simulation method derived from Verlet’s integration scheme and combined distance constraints. The framework of PBD can be seen here. Specifically, using distance and angular constraints, modifying vertices’ position directly and solving [constraints](#) with some iterations. This paper is easier to read than PBD, but the ideas appear here and pseudo codes are presented. I recommend reading this before read PBD.
 - “*Large steps in cloth simulation*” [1] solved implicit integration with [constraints](#) by [conjugate gradient method](#) for off-line simulation. The scheme isn’t used at PBD, but this one gives us a perspective of present physical simulations.
 - “*Projective Dynamics: Fusing Constraint Projections for Fast Simulation*” [11] provided a position-based method that uses energy formulation and local/global solver. The method has a local Jacobi-like solver and a linear global equation one. The solvers enable robust and fast simulation without safeguards against singular or indefinite Hessians. If you want to understand state-of-the-art physics simulation methods, including PBD, it’s better to read this.
 - “*ADMM \subseteq projective dynamics: fast simulation of general constitutive models*” [12] is worth reading because ADMM is actively researched now because of its robustness, parallelizability, and simplicity.
3. These papers offer interesting discussions around PBD, deepen your understanding of PBD, or description of basic physical simulation scheme.
 - “*Constraint Methods for Neural Networks and Computer Graphics*” [16] describes the constraint methods for neural networks and computer graphics. It may not be easy to read because of 150 pages. But, if you have time, it’s more worth reading this paper than some papers published before this one.
 - “*Example-based elastic materials*” [9] provides a concept of the elastic manifold and optimization method for deforming into an artist-desirable state. However,

this paper lacks reference to the manifold projection methods that are apparently well-known in the geometric optimization field. This paper helps us understand Projective dynamics, but I don't know Projective Dynamics's relevance with (X)PBD for now.

- “*Fast simulation of mass-spring systems*”[10] describes the local/global type solver to the mass-spring system clearly. Thus this paper helps us understand the variant solvers.
 - “*Interactive simulation of elastic deformable materials*”[6] introduces physical parameters into constrained dynamics; the spirit is inherited by XPBD and there is an interesting discussion about the integrator. But I think this paper does explain the concept poorly, e. g. the integrator provided here, equation (20) lack of explanation, etc. Therefore, this one classified here.
 - “*Nucleus: Towards a unified dynamics solver for computer graphics*”[19] is a good introduction to constrained dynamics because it shows its implementation aspect. However, it doesn't describe how constraints are resolved, so it isn't full-contained.
 - “*Robust treatment of collisions, contact and friction for cloth animation*”[20]'s scheme separates physical simulation into internal parts and external parts. Therefore, we can choose the internal modeling(e.g. mass-spring) and the external modeling(e.g. collision repulsion, friction, or gravity) independently. However, the scheme is not directly related to PBD.
 - “*Strain Based Dynamics*”[18]. The formulation of the strain tensor in XPBD seems to be based on “Interactive Simulation of Elastic Deformable Materials”(2006) rather than this paper. However, the formulations described here are easy to understand if you are familiar with PBD and strain tensor.
 - “*Geometric, Variational Integrators for Computer Animation*”[5] presents the variational integrator from the Lagrangian/Hamiltonian physics that preserves linear/angular momenta. Its conservative quantities will be more important in fields such as robotics or accurate physical computation. But, this knowledge may be useless if you only want to understand (X)PBD.
 - “*Efficient simulation of inextensible cloth*”[17] treated the constrained system as globally linearized form and solved with a direct approach at each iteration.
4. These ones have historical value, but deeper discussions are done in other papers.
- “*Elastically deformable models*”[21] brought the formulation of elastic bodies to computer graphics.



B Glossary

B.1 symbols

B.2 terms

conjugate gradient method

This method, abbreviated as CG method is used linear equations that form is $A\mathbf{x} = \mathbf{b}$. This method often has high computational cost .

constraint

At the (X)PBD, constraint is relationship among arbitrary vertices what we want to keep during simulation. It can express not only between two vertices relation, e.g. distance a vertex to another one, but among more than three vertices, e.g. volume of the tetrahedron .

elastic-body

This is an object that resists deformation and returns to its original shape when that influence or force is removed. Sometimes, the term refers to objects with high stiffness(e.g. steel wire). .

Iteration

In computer science, iteration is the process of repeating a series of instructions multiple times. Especially at (X)PBD, the part of physical solver which treats [constraints](#) is called iteration .

Lagrangian mechanics

This is one of the physics theories that conserves momentum in addition to inertia. Variational integration is a crucial concept in this theory. Hamiltonian mechanics is also known as a more generalized form than this theory. .

soft-body

This is an object that deforms by external force. The term is often compared to "Rigid body" which refers to an undeformable object. .

References

- [1] Baraff, D., Witkin, A.: Large steps in cloth simulation. In: Proceedings of the 25th Annual Conference on Computer Graphics and Interactive Techniques. SIGGRAPH '98, pp. 43–54. Association for Computing Machinery, New York, NY, USA (1998). <https://doi.org/10.1145/280814.280821> . <https://doi.org/10.1145/280814.280821>
- [2] Jakobsen, T.P.: Advanced character physics. (2003). <https://api.semanticscholar.org/CorpusID:5102710>
- [3] Teschner, M., Heidelberger, B., Müller, M., Gross, M.: A versatile and robust model for geometrically complex deformable solids. In: Proceedings Computer Graphics International, 2004., pp. 312–319 (2004). <https://doi.org/10.1109/CGI.2004.1309227>
- [4] Müller, M., Heidelberger, B., Hennix, M., Ratcliff, J.: Position based dynamics. *J. Vis. Comun. Image Represent.* **18**(2), 109–118 (2007) <https://doi.org/10.1016/j.jvcir.2007.01.005>
- [5] Kharevych, L., Yang, W., Tong, Y., Kanso, E., Marsden, J.E., Schröder, P., Desbrun, M.: Geometric, variational integrators for computer animation. In: Proceedings of the 2006 ACM SIGGRAPH/Eurographics Symposium on Computer Animation. SCA '06, pp. 43–51. Eurographics Association, Goslar, DEU (2006)
- [6] Servin, M., Lacoursière, C., Melin, N.: Interactive simulation of elastic deformable materials. (2006). <https://api.semanticscholar.org/CorpusID:16851165>
- [7] Macklin, M., Müller, M., Chentanez, N.: Xpbd: position-based simulation of compliant constrained dynamics. In: Proceedings of the 9th International Conference on Motion in Games. MIG '16, pp. 49–54. Association for Computing Machinery, New York, NY, USA (2016). <https://doi.org/10.1145/2994258.2994272> . <https://doi.org/10.1145/2994258.2994272>
- [8] Macklin, M., Storey, K., Lu, M., Terdiman, P., Chentanez, N., Jeschke, S., Müller, M.: Small steps in physics simulation. In: Proceedings of the 18th Annual ACM SIGGRAPH/Eurographics Symposium on Computer Animation. SCA '19. Association for Computing Machinery, New York, NY, USA (2019). <https://doi.org/10.1145/3309486.3340247> . <https://doi.org/10.1145/3309486.3340247>
- [9] Martin, S., Thomaszewski, B., Grinspun, E., Gross, M.: Example-based elastic materials. In: ACM SIGGRAPH 2011 Papers. SIGGRAPH '11. Association for Computing Machinery, New York, NY, USA (2011). <https://doi.org/10.1145/1964921.1964967> . <https://doi.org/10.1145/1964921.1964967>

- [10] Liu, T., Bargteil, A.W., O'Brien, J.F., Kavan, L.: Fast simulation of mass-spring systems. *ACM Trans. Graph.* **32**(6) (2013) <https://doi.org/10.1145/2508363.2508406>
- [11] Bouaziz, S., Martin, S., Liu, T., Kavan, L., Pauly, M.: *Projective Dynamics: Fusing Constraint Projections for Fast Simulation*, 1st edn. Association for Computing Machinery, New York, NY, USA (2023). <https://doi.org/10.1145/3596711.3596794>
- [12] Narain, R., Overby, M., Brown, G.E.: Admm \subseteq projective dynamics: fast simulation of general constitutive models. In: *Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer Animation. SCA '16*, pp. 21–28. Eurographics Association, Goslar, DEU (2016)
- [13] Bender, J., Müller, M., Macklin, M.: A survey on position based dynamics, 2017. In: *Proceedings of the European Association for Computer Graphics: Tutorials. EG '17*. Eurographics Association, Goslar, DEU (2017). <https://doi.org/10.2312/egt.20171034> . <https://doi.org/10.2312/egt.20171034>
- [14] Witkin, A., Fleischer, K., Barr, A.: Energy constraints on parameterized models. *SIGGRAPH Comput. Graph.* **21**(4), 225–232 (1987) <https://doi.org/10.1145/37402.37429>
- [15] Barzel, R., Barr, A.H.: A modeling system based on dynamic constraints. *SIGGRAPH Comput. Graph.* **22**(4), 179–188 (1988) <https://doi.org/10.1145/378456.378509>
- [16] Platt, J.C.: *Constraint methods for neural networks and computer graphics*. PhD thesis, USA (1990). UMI Order No: GAX90-00594
- [17] Goldenthal, R., Harmon, D., Fattal, R., Bercovier, M., Grinspun, E.: Efficient simulation of inextensible cloth. *ACM Trans. Graph.* **26**(3), 49 (2007) <https://doi.org/10.1145/1276377.1276438>
- [18] Müller, M., Chentanez, N., Kim, T.-Y., Macklin, M.: Strain based dynamics. In: *Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer Animation. SCA '14*, pp. 149–157. Eurographics Association, Goslar, DEU (2015)
- [19] Stam, J.: Nucleus: Towards a unified dynamics solver for computer graphics. In: *2009 11th IEEE International Conference on Computer-Aided Design and Computer Graphics*, pp. 1–11 (2009). <https://doi.org/10.1109/CADCG.2009.5246818>
- [20] Bridson, R., Fedkiw, R., Anderson, J.: Robust treatment of collisions, contact and friction for cloth animation. *ACM Trans. Graph.* **21**(3), 594–603 (2002) <https://doi.org/10.1145/566654.566623>
- [21] Terzopoulos, D., Platt, J., Barr, A., Fleischer, K.: *Elastically*

- deformable models. SIGGRAPH Comput. Graph. **21**(4), 205–214 (1987) <https://doi.org/10.1145/37402.37427>
- [22] Barzel, R., Barr, A.H.: A modeling system based on dynamic constraints. SIGGRAPH Comput. Graph. **22**(4), 179–188 (1988) <https://doi.org/10.1145/378456.378509>
- [23] Müller, M., Heidelberger, B., Teschner, M., Gross, M.: Meshless deformations based on shape matching. ACM Trans. Graph. **24**(3), 471–478 (2005) <https://doi.org/10.1145/1073204.1073216>
- [24] Müller, M., Kim, T., Chentanez, N.: Fast simulation of inextensible hair and fur. (2012). <https://doi.org/10.2312/PE/vriphys/vriphys12/039-044>
- [25] Kim, T., Chentanez, N., Müller, M.: Long range attachments - a method to simulate inextensible clothing in computer games, pp. 305–310 (2012). <https://doi.org/10.2312/SCA/SCA12/305-310>
- [26] Macklin, M., Müller, M.: Position based fluids. ACM Trans. Graph. **32**(4) (2013) <https://doi.org/10.1145/2461912.2461984>
- [27] Bender, J., Koschier, D., Charrier, P., Weber, D.: Position-based simulation of continuous materials. Computers & Graphics **44**, 1–10 (2014) <https://doi.org/10.1016/j.cag.2014.07.004>
- [28] Macklin, M., Müller, M., Chentanez, N., Kim, T.-Y.: Unified particle physics for real-time applications. ACM Trans. Graph. **33**(4) (2014) <https://doi.org/10.1145/2601097.2601152>
- [29] Müller, M., Chentanez, N., Kim, T.-Y., Macklin, M.: Air meshes for robust collision handling. ACM Trans. Graph. **34**(4) (2015) <https://doi.org/10.1145/2766907>
- [30] Tournier, M., Nesme, M., Gilles, B., Faure, F.: Stable constrained dynamics. ACM Trans. Graph. **34**(4) (2015) <https://doi.org/10.1145/2766969>
- [31] Macklin, M., Erleben, K., Müller, M., Chentanez, N., Jeschke, S., Makoviyshuk, V.: Non-smooth newton methods for deformable multi-body dynamics. ACM Trans. Graph. **38**(5) (2019) <https://doi.org/10.1145/3338695>
- [32] Müller, M., Macklin, M., Chentanez, N., Jeschke, S., Kim, T.-Y.: Detailed rigid body simulation with extended position based dynamics. In: Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer Animation. SCA '20. Eurographics Association, Goslar, DEU (2020). <https://doi.org/10.1111/cgf.14105> . <https://doi.org/10.1111/cgf.14105>
- [33] Macklin, M., Muller, M.: A constraint-based formulation of stable neo-hookean

materials. In: Proceedings of the 14th ACM SIGGRAPH Conference on Motion, Interaction and Games. MIG '21. Association for Computing Machinery, New York, NY, USA (2021). <https://doi.org/10.1145/3487983.3488289> .
<https://doi.org/10.1145/3487983.3488289>

- [34] Müller, M., Macklin, M., Chentanez, N., Jeschke, S.: Physically based shape matching. *Computer Graphics Forum* **41**, 1–7 (2023) <https://doi.org/10.1111/cgf.14618>