Review of Haptic Rendering Techniques for Hip Surgery Training

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Keywords: Haptics, Force-Feedback, Virtual Reality, Surgery Simulation.

Abstract

In this review paper, we discuss haptic rendering techniques that can be used for hip surgery training. In the context of surgery, the simulation requires high quality of feedback forces and the interaction with the virtual environment must be synchronized in real time. Several studies were presented since the 90s to solve collision detection problem and force feedback computation. In this review paper, we classify haptic rendering techniques under two categories: methods of direct force-feedback computation, and proxy based methods. In the first category, the force is calculated and sent directly to the haptic device once the penetration measure is found. In contrast the proxy based techniques try to follow the haptic device using a proxy or "god-object" which is limited to the surface of rigid objects in the virtual environment, then compute the feedback force based on the behavior of this proxy. Under each category, we present the different techniques and discuss their benefits and disadvantages in the light of surgery training.

Introduction

Virtual Reality (VR) in combination with haptic feedback is a powerful technology for training medical residents in surgical procedures[18]. While such simulators have proven their benefits for training of minimally invasive surgeries, such as laparoscopic or arthroscopic procedures, there

[18] Escobar-Castillejos, D., Noguez, J., Neri, L., Magana, A., & Benes, B. (2016). A review of simulators with haptic devices for medical training. Journal of medical systems, 40(4), 104. https://doi.org/10.1007/s10916-016-0459-8

barely exist haptic VR training possibilities for procedures in which high forces occur. Especially in the orthopedic field where several hundred thousand of joint prostheses are implanted worldwide annually. Therefore young surgeons would greatly benefit from haptic VR training purposes. While only visual training simulations exist in this area, the missing realistic haptic feedback hinders these simulations from unfolding their complete potential. However, providing realistic haptic feedback for orthopedic joint implant procedures challenges the capabilities of current haptic feedback devices and haptic rendering technologies alike. Especially, the occurring forces and torques during the individual surgical steps are largely unknown. Pioneering work in this field was performed by Pelliccia et al.[19] who assessed the occurring forces and torques during acetabulum reaming, which is one step during hip joint replacement surgery. Based on this data Kaluschke et al.[20] were able to implement a haptic rendering algorithm simulating the forces and torques during acetabulum reaming. Knopp et al.[21] were able to utilize this haptic rendering algorithm by using a KUKA iiwa LBR robot. With this robot approach, the occurring average reaming forces of up to 160 N[19] could actually be transmitted to the training surgeon. These combined efforts lead to a research prototype capable of simulating acetabulum reaming in VR with realistic haptic feedback[22].

However, the haptic simulation of the acetabulum reaming is a comparably easy step in relation to the other surgical task in hip replacement surgery: (1) implanting the pan; (2) reaming the femur; (3) implanting the shaft; (4) cutting the femoral head. The first three steps require hammering where very large impact forces are occurring, posing completely new challenges to the haptic rendering techniques and hardware devices alike. In an initial step, the existing haptic rendering techniques have to be analyzed in order to also develop haptic feedback for the steps that involve hammering.

By "haptic rendering techniques", we mean the methods and algorithms which compute a signal to be rendered as haptic feedback to the user through a force-feedback device. This leaves out the problems of: i) creating the 3D model(s) of the virtual environment, ii) measuring and applying material properties, iii) detecting collisions between 3D objects, and iv) computing the changes in the model due to object deformation or material abrasion. We do not discuss these issues of force regulation and actuator control of the force-feedback device either.

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[19] Pelliccia, L., Lorenz, M., Heyde, C. E., Kaluschke, M., Klimant, P., Knopp, S., ... & Zachmann, G. (2020). A cadaver-based biomechanical model of acetabulum reaming for surgical virtual reality training simulators. Scientific Reports, 10(1), 1-12. https://doi.org/10.1038/s41598-020-71499-5

[20] Kaluschke, M., Weller, R., Hammer, N., Pelliccia, L., Lorenz, M., & Zachmann, G. (2020, March). Realistic Haptic Feedback for Material Removal in Medical Simulations. In 2020 IEEE Haptics Symposium (HAPTICS) (pp. 920-926). IEEE. https://doi.org/10.1109/HAPTICS45997.2020.ras.HAP20.74.13165668

[21] Knopp, S., Lorenz, M., Pelliccia, L., & Klimant, P. (2018, March). Using industrial robots as haptic devices for vr-training. In 2018 IEEE conference on virtual reality and 3D user interfaces (VR) (pp. 607-608). IEEE. https://doi.org/10.1109/VR.2018.8446614

[22] Kaluschke, M., Weller, R., Zachmann, G., Pelliccia, L., Lorenz, M., Klimant, P., ... & Móckel, F. (2018, March). Hips-a virtual reality hip prosthesis implantation simulator. In 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) (pp. 591-592). IEEE. https://doi.org/10.1109/VR.2018.8446370

Our analysis is based on a thorough review of scientific publications discussing haptic rendering techniques, both in a general case and applied to surgery simulation. In the ensuing discussion, the authors' own hands-on experience with the different techniques is reported as well.

Objectives

In our previous research, we aimed at solely simulating the acetabular reaming using haptic feedback. To achieve this, we developed a novel haptic rendering technique that combines ideas of penalty and proxy-based methods[20]. In brief terms, we represent the reamer and acetabulum as a collection of poly-disperse, non-overlapping spheres. The force is computed based on a proxy tool that follows the user input, but doesn't penetrate the acetabulum, which we guarantee using continuous collision detection (see Figure 10). Torques are computed using the penalty formula with a single contact point of the proxy on the acetabulum surface. The material removal is simulated by updating the sphere collections of the acetabulum at runtime.

In the continuation of our research, we still intend to simulate acetabular reaming. Consequently, we will be able to build upon the previously developed algorithm and improve it. In particular, we aim at simulating the proxy motion more realistically and consequently allowing for multiple contact points and a more realistic torque simulation. However, we still need to stay within the 1 kHz update frequency to allow stable operation of the haptic device.

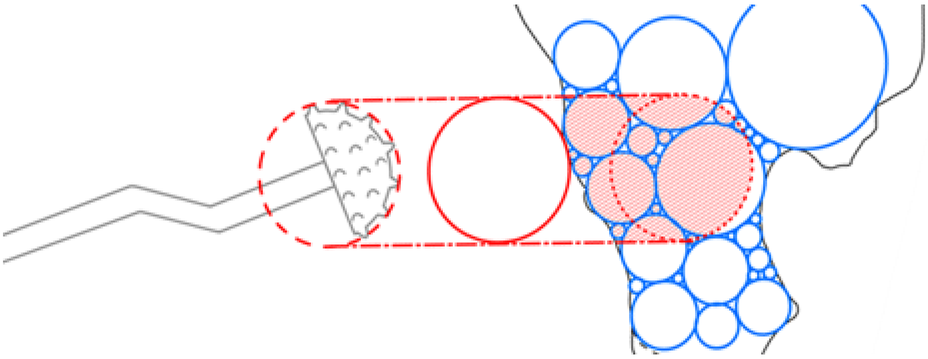

Figure 10. The acetabulum is represented as a set of non-overlapping spheres (blue). The hip reamer (red) does not penetrate the hip, but is bound to its surface.

Haptic Rendering Techniques

For the sake of clarity, we define two categories of haptic rendering techniques.

The first category gathers the techniques which consist in directly calculating a force/torque to be applied to the force-feedback device. Within that first category, we will describe i) the penalty method, ii) the impulse method, and iii) the event-driven method.

The second category is dedicated to techniques which make use of a proxy, also called "god-object", and derive the haptic feedback from the behavior of that proxy. The motion of the proxy can be computed either geometrically, or by using time-stepping physics simulation.

Penalty Method

Penalty-based approach works in two states: "no contact" state is active when there is always positive distance between objects; and "resting contact" state is active when objects interpenetrate. In the latter case, the method calculates forces by penalizing interpenetration proportional to the depth of penetration.

The inter-penetration problem is often modeled using a spring-damper mechanism. Feedback forces applied are proportional to the amount of penetration of the haptic device into the object in contact[23]. In case of 3-DoF (3 degrees of freedom) modeling, a point-probe interaction is used, and the operator feels only forces of contact in the virtual environment. In contrast, when the 6-DoF modeling is implemented, a more complex object-probe interaction is used, and the operator feels forces and torques upon contact in the virtual environment[24]. The forces are easy to calculate when using simplified geometries like spheres and planes. Upon collision, the method starts by detecting the nearest surface then calculates the distance of penetration. Once the distance is found, the force can be easily calculated using Hooke's law[25] [8]. The direction of the feedback forces should be normal to the surface of contact; when modeling with spheres, the force direction is equivalent to the vector starting from sphere center and going through the haptic interaction point (HIP)[26].

The penalty method is a popular and easy approach that is widely used in haptic rendering applications. McNeely et al.[27] implemented the penalty method using the voxel-based approach for 6-DoF haptic rendering in 1999. The authors defined voxel maps as 3D grids in space and used it to represent virtual objects. The user can interact with the voxel based environment using small object-probes modeled as pointshells. Sagardia[24] stated that the Voxmap PointShell (VPS) algorithm is one of the most used implementation of penalty-based method.

As stated in[26], this method has multiple drawbacks. It is hard to choose the right surface upon contact. The corners of objects feel sharp because of the discontinuity of forces. In addition, when facing a thin object, this method cannot generate enough forces to prevent the haptic device from going through the object. Then in that case, the nearest surface will be changed and the operator will be pushed out of the object because of opposite forces. Other problems for the penalty-based methods are listed in[24], like possible visual overlap, and irregular distribution of the stiffness.

If the contact between objects is not simple, it is hard to identify a single penetration depth and many points of contact are considered. For each contact point, a penalty force is associated based on the relevant penetration depth. If multiple penalty forces are in the same direction, the forces sum up and a "stiffness accumulation" occurs. Due to stiffness accumulation, the feedback forces

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[23] Ruspini, D. C., Kolarov, K., & Khatib, O. (1997, August). The haptic display of complex graphical environments. In Proceedings of the 24th annual conference on Computer graphics and interactive techniques (pp. 345-352). Available online at: https://rb.gy/gkex6g last accessed 14.10.2020.

[24] Erasun, S. (2019). Virtual Manipulations with Force Feedback in Complex Interaction Scenarios (Doctoral dissertation, Technische Universität München.

[25] Hooke's Law. https://en.wikipedia.org/wiki/Hooke%27s_law last accessed on 1.9.2020.

[26] Zilles, C. B., & Salisbury, J. K. (1995, August). A constraint-based god-object method for haptic display. In Proceedings 1995 ieee/rsj international conference on intelligent robots and systems. Human robot interaction and cooperative robots (Vol. 3, pp. 146-151). IEEE. https://doi.org/10.1109/IROS.1995.525876

[27] McNeely, W. A., Puterbaugh, K. D., & Troy, J. J. (2005). Six degree-of-freedom haptic rendering using voxel sampling. In ACM SIGGRAPH 2005 Courses (pp. 42-es). https://doi.org/10.1109/IROS.1995.525876

may be exaggerated, and the haptic device will potentially suffer from stability problems. Scaling down stiffness by the number of contact points is usually used to tackle this problem, but this introduces large penetration issues for complex objects. Xu and Barbič[28] proposed a spatially-varying adaptive stiffness method. Using the Gauss map of contact normals, the proposed method guarantees uniform distribution of stiffness in all contact directions. This way, they were able to avoid unwanted penetration of objects and enhance the virtual coupling saturation.

Kim and Park[29] implemented penalty based method for dental implant surgery training. Using PointShell representation for bones and signed distance field for the drilling tool, authors were able to simulate arbitrarily shaped tools having multiple contacts with the bone. During the collision, the bone starts losing voxels in real time relative to the thrust force applied by the surgeon while the feedback forces are accurately and efficiently calculated using the distance field encoded in the tool.

Impulse Method

Brian Mirtich and John Canny[30] proposed the impulse based approach for rigid-body simulation first in 1994. The impulse method is known to be simple and robust at the same time. It is fast enough to work in real time simulation. One single model is used to represent all kinds of contact (collision, rolling and sliding). The authors treated each contact as frequent small collisions called microcollisions. Unlike constraint-based methods (see below under "proxy method"), the impulse method does not apply constraints on the object configuration and does not limit the movement of the proxy. The collision detection implements the closest feature algorithm: it computes the possible times to collision and stores them in a list with prioritized sorting. This sorting leads to dynamic evolution step. If the distance between close features is less than set threshold, a collision is detected. Hence, the impulse force is only applied if the difference of velocity between two objects has a magnitude in the normal direction to the surface of contact.

The method considered three assumptions for simplification: First, collision time is relatively negligible compared to movement duration of the objects in virtual environment. In this case, the impulse method imposes instantaneous influence on the linear and angular velocity upon contact rather than only change on acceleration. Then, the authors considered Poisson's hypothesis which helps for resolving collisions. And finally, the Coulomb's friction theory is applied to ensure the relation between tangential and normal forces.

The impulse method has been implemented by Constantinescu et al.[31] for haptic rendering. They proposed a hybrid algorithm to improve stability and rigidity perception upon interaction with

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[28] Xu, H., & Barbič, J. (2016). Adaptive 6-dof haptic contact stiffness using the gauss map. IEEE transactions on haptics, 9(3), 323-332. https://doi.org/10.1109/TOH.2016.2558185.

[29] Kim, K., & Park, J. (2009, November). Virtual bone drilling for dental implant surgery training. In Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology (pp. 91-94). https://doi.org/10.1145/1643928.1643950.

[30] Mirtich, B., & Canny, J. (1994). Impulse-based dynamic simulation. California: Computer Science Division (EECS), University of California.

[31] Constantinescu, D., Salcudean, S. E., & Croft, E. A. (2005). Haptic rendering of rigid contacts using impulsive and penalty forces. IEEE transactions on robotics, 21(3), 309-323. https://doi.org/10.1109/TRO.2004.840906.

objects in virtual environment. The proposed method applies impulsive forces upon contact and rely on penalty and friction forces during contact. A suitable controller is used to send computed forces directly to the force-feedback device. The authors presented experimental results that shows increased contact stability on a 2D system, including passivity.

Wang et al.[32] also used the impulse based approach for haptic simulation of bone burring. The burring tool is modeled based on real burr geometry. In their study, they assume that both burring tool and bone materials are rigid bodies. In addition, the authors assume that the velocity is directly affected at the moment of contact as mentioned in[30]. They considered that contact forces can be split into resistance and friction. The friction model includes static and dynamic friction. In addition, a 3D vibration model is proposed to mimic the vibration forces applied to the burring tool. The dynamics of impulse based method allows them to evaluate contact forces of interaction between rigid bones and the surgical instruments. Finally, the sum of the computed forces is transmitted back to the haptic device. An efficient bone removal scheme was also developed in order to provide the user with a realistic visual feedback for the training process. The results presented by Wang et al. show the ability of the impulse based method to simulate feedback forces in real time which are consistent with real bone burring operations.

Event-Driven Method

The event-driven method was first introduced by Kuchenbecker et al.[33] in 2006. The authors aimed to improve the realism of interacting with virtual environments, especially for wooden objects. They added a transient perturbation signal to the feedback force. Adding this perturbation makes virtual objects feel like real wood on a foam substrate, while it is rated as feeling unrealistic with just the penalty-based forces.

Similarly to the penalty based approach, the event-driven method applies standard position feedback forces. In addition, it also applies pre-defined impact transients upon contact detection with a rigid surface. High frequency transient forces help stimulating the human's perception to feel a high stiffness while low-bandwidth closed loop forces are used to capture the user's motion. An exponentially decaying sinusoidal forces is suggested with a frequency dependent on material type.

Kuchenbecker et al. showed how such forces improve the perception of virtual stiffness of objects, by using actual recordings with accelerometers on real material as transient force signals. They demonstrated that users could discriminate between different materials applied to a virtual wall. However, they did not explore the application of their method beyond a single degree of freedom.

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[32] Wang, Q., Chen, H., Wu, W., Qin, J., & Heng, P. A. (2011). Impulse-based rendering methods for haptic simulation of bone-burring. IEEE transactions on haptics, 5(4), 344-355. https://doi.org/10.1109/TOH.2011.69

[33] Kuchenbecker, K. J., Fiene, J., & Niemeyer, G. (2006). Improving contact realism through event-based haptic feedback. IEEE transactions on visualization and computer graphics, 12(2), 219-230. https://doi.org/10.1109/TVCG.2006.32

Sreng et al.[34] used impact events to enhance the haptic rendering with 6-DoF. They chose to apply high frequency force patterns in addition to the standard force feedback provided by their rigid-body simulation method (see below). The proposed solution distinguishes between two types of contact; the continuous contact like friction, and the discrete event based contact like impact and detachment. The generated contact states and events only rely on the position of objects in the virtual environment. The forces related to friction were generated using the tangential velocity of moving bodies. On the other hand, the impact and detachment forces were generated based on the normal velocity between two objects at point of contact. The authors did not conduct a user study in order to evaluate the relevance of their method.

In our review of the state-of-the-art, we could not find any use of the event-driven method in the context of surgery simulation.

Proxy Method

In their paper of 1995, Zilles and Salisbury [26] propose a "constraint based" method as a way to address the limitations of the penalty method. They introduce the concept of a "god-object" or "proxy", which represents the virtual placement of the tool attached to the haptic device, but limited by objects in the virtual environment. If no collision is detected, then the proxy is exactly moving with the haptic device and no force feedback is applied. Upon contact, collision forces and torques are generated by a dampened spring between the god-object and the control point of the haptic device (the "Haptic Interaction Point" or "HIP").

In 2006, Kang et al.[35] filed a patent for the proxy method, which was awarded and is now owned by the company Mako Surgical Corp. Although their application is clearly focused on surgery, the patent claims are much more general and cover potentially all applications. Nevertheless, since there is clear prior art[36], the patent could in no case give rise to an infringement action, and is rather a measure of protection. A very similar patent was filed by Petersik et al.[36] in 2008 for the Hamburg Medical University, including a method for material removal.

The placement of the proxy can be determined using two different approaches: i) geometrically or ii) through rigid-body dynamics simulation.

Geometric Placement of the Proxy

In [26], the authors consider a surface as an active constraint if the line that connects the proxy and the HIP pass through it. When the HIP faces an obstacle, the proxy is limited by the active

[34] Sreng, J., Bergez, F., Legarrec, J., Lécuyer, A., & Andriot, C. (2007, November). Using an event-based approach to improve the multimodal rendering of 6DOF virtual contact. In Proceedings of the 2007 ACM symposium on Virtual reality software and technology (pp. 165-173). https://doi.org/10.1145/1315184.1315215

[35] Kang, H., Quaid, A. E., & Moses, D. (2013). U.S. Patent No. 8,571,628. Washington, DC: U.S. Patent and Trademark Office. Available at: https://rb.gy/g30ild last accessed 14.10.2020

[36] Petersik, A., Hohne, K. H., Pflesser, B., Pommert, A., & Tiede, U. (2013). U.S. Patent No. 8,396,698 B2. Washington, DC: U.S. Patent and Trademark Office. Available online at: https://rb.gy/gvv2pl last accessed 14.10.2020.

constraints, though the haptic device can still penetrate into the object. Using Lagrange multipliers, they are able to calculate the position of the proxy object, so that it stays at the surface of the obstacles.

Ruspini et al.[23] represent the proxy as a mass-less sphere that can be moved along the objects in the virtual environment. Their implementation provides modeling for contact constraints, surface shading, texture and friction. To calculate the position of the proxy during contact, the authors consider several contact half-planes where each constraint plane limits the movement of the proxy to the half space above the plane.

Collision detection can be discrete or continuous. In the former, the movement is sampled to detect inter-penetration between object. In this case, it is possible to miss the collision, especially when having thin objects or high velocity of movement. On the other hand, in continuous collision detection, in-between position interpolation is done where the calculation of the time of first contact between objects is part of the algorithm. In their study, Redon et al.[37] presented a fast continuous collision detection using OBB (Object Bounding Boxes) hierarchies, with integration of arbitrary in-between rigid motions and interval arithmetic technique[38]. In another paper[39], the authors introduced the concept of algebraic in-between motions method where it is possible to compute the first collision time by solving a cubic polynomial equation (degree 3) at most. Using screwing-based motions, they were able to break-down the collision problem to multiple cases and resolve the equation accordingly.

Ortega et al.[40] generalized the constraint-based method and applied it for 6-DoF haptic rendering. They proposed efficient computation algorithm for the force rendering using a separate asynchronous thread. This separation helps them to easily achieve the needed update rate of 1 kHz. The moving position of the proxy and the force feedback are calculated using continuous collision detection and constraint-based quasi-statics. They were able to avoid force artifacts found in other methods.

In our previous research, we applied the continuous collision detection technique in order to determine the behavior of the proxy (Figure 1)[20].

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[37] Redon, S., Kheddar, A., & Coquillart, S. (2002, September). Fast continuous collision detection between rigid bodies. In Computer graphics forum (Vol. 21, No. 3, pp. 279-287). Oxford, UK: Blackwell Publishing, Inc. https://doi.org/10.1111/1467-8659.t01-1-00587

[38] Interval arithmetic. https://en.wikipedia.org/wiki/Interval_arithmetic last accessed 7.9.2020

[39] Redon, S., Kheddar, A., & Coquillart, S. (2000, April). An algebraic solution to the problem of collision detection for rigid polyhedral objects. In Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No. 00CH37065) (Vol. 4, pp. 3733-3738). IEEE. https://doi.org/10.1109/ROBOT.2000.845313

[40] Ortega, M., Redon, S., & Coquillart, S. (2007). A six degree-of-freedom god-object method for haptic display of rigid bodies with surface properties. IEEE transactions on visualization and computer graphics, 13(3), 458-469. https://doi.org/10.1109/TVCG.2007.1028

Rigid-body dynamics simulation

In 2000, Ruspini and Khatib[41] proposed a new haptic rendering technique consisting in "attaching the virtual proxy to a virtual object", which is itself part of a simulated dynamic environment. As a benefit, the "virtual tool […] is no longer restricted to simple point or sphere". This technique transfers the complexity of haptic rendering to that of rigid-body dynamic simulation, which needs to be completed at a frequency compatible with haptic rates.

The research on fast rigid-body dynamics simulation has been driven by the needs of the graphics computing community since the late 1980s[42]. It has resulted in the development of the real-time physics simulation capabilities integrated in modern computer game engines. Today, the development of a virtual reality system could almost be reduced to choosing between several physics engines and tuning the stiffness and damping parameters of the proxy. However, even GPU-accelerated physics engines are not yet quite up to the task of handling complex object geometries with a high precision at haptic rates. Therefore, a lot of effort is still needed in order to address the challenges in each specific application domain.

For example, Syllebranque and Duriez[43] applied the rigid-body simulation technique to a dental implantology training system. They used the VPS representation of the jawbone and drill together with a 3D distance map in order to compute collision constraints. Then they applied physical simulation in order to update the position of the proxy. Their results demonstrated how the operation process requires increasing forces at the beginning while drilling the cortical part (up to 15N during 6 seconds). Then, they were able to reproduce the cortical breakthrough which must be avoided by surgeons since it could lead to damaging facial nerves.

Discussion

The ultimate goal of any training system is to achieve a good "transfer of training", i.e. the ability of the trainees to learn skills in the virtual environment and apply them successfully in real conditions[44]. In their EAES guidelines[45], Carter et al. define a number of validity criteria for virtual

[41] Ruspini, D., & Khatib, O. (2000). A framework for multi-contact multi-body dynamic simulation and haptic display. In Advances in Robot Kinematics (pp. 175-186). Springer, Dordrecht. https://doi.org/10.1007/978-94-011-4120-8_19

[42] Baraff, D. (1994, July). Fast contact force computation for nonpenetrating rigid bodies. In Proceedings of the 21st annual conference on Computer graphics and interactive techniques (pp. 23-34). https://doi.org/10.1145/192161.192168

[43] Syllebranque, C., & Duriez, C. (2010, January). Six degree-of freedom haptic rendering for dental implantology simulation. In International Symposium on Biomedical Simulation (pp. 139-149). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-11615-5_15

[44] Vander Poorten, E. B., Perret, J., Muyle, R., Reynaerts, D., Vander Sloten, J., & Pintelon, L. (2014). To Feedback or not to Feedback–the Value of Haptics in Virtual Reality Surgical Training. In Proc. Int. Conf. of the European Association of Virtual and Augmented Reality (EuroVR). http://dx.doi.org/10.2312/eurovr.20141356

[45] Carter, F. J., Schijven, M. P., Aggarwal, R., Grantcharov, T., Francis, N. K., Hanna, G. B., & Jakimowicz, J. J. (2005). Consensus guidelines for validation of virtual reality surgical simulators. Surgical Endoscopy and Other Interventional Techniques, 19(12), 1523-1532. https://doi.org/10.1007/s00464-005-0384-2

reality surgical simulators. The first level is the “face validity”, which assesses the realism of the user experience, and it’s the only level which can be addressed directly by the haptic rendering.

As explained above, of all haptic rendering techniques the penalty method is the easiest to implement, but it has severe drawbacks. In particular for the purpose of hip surgery simulation, behaviors like snapping through thin bone structures or swapping between contact normals are not acceptable. In addition, the penalty method does not prevent visual interpenetration, which would disrupt the face validity of the training system. Especially in the case of hammering, we can expect the high transient forces to create all sorts of artifacts with the penalty method.

The logical step for overcoming the limitations of the penalty method is to introduce a proxy. Moreover, the virtual coupling with the proxy provides an efficient solution for improving the stability of the force-feedback device. In their paper[46], Sagardia and Hulin compared penalty and constraint (i.e. proxy) methods and showed how the constraint-based algorithm with a stiffness under the maximum possible value, provides the most realistic feedback perception.

However, the proxy method also reduces all haptic information down to a single force/torque wrench applied at the HIP, and therefore loses both the transient signals and the detailed configuration of contact, which is not desirable. More to the point, we can expect that hitting a spring-damper system does not feel like hammering on bone.

The event-driven method is precisely focused on the transient signals. It is recognized as giving the most realistic feedback on material properties, thanks to its relying on actual measurements performed on real objects. Initially, the method was demonstrated on one degree-of-freedom only, and combined with penalty for the static feedback (although in their publication, Kuchenbecker et al. use a proxy for determining the penetration vector[33]). Very little work was done on its extension to more complex setups. Therefore, it is unclear whether a combination of the proxy and event-driven methods are liable to provide a significant improvement of the user experience.

The impulse method would appear to be the best suited to render rigid contact, and handle high transient forces. Indeed, by transferring the problem into the speed domain, it generates impulse forces that should brake the motion of the impacting tool down to zero. In their very impressive body of work, Wang et al. demonstrate that the impulse method can be applied successfully to the interaction with bone material[32]. However, our prior experience leads us to suspect a number of limitations to their work. Firstly, the implementation seems computationally complex, forcing them to compromising between the cycle time and the model resolution. Secondly, their approach is bound to generate many tuning parameters, with no explicit procedure for setting them. Finally, they validated their implementation on a 3-DoF force-feedback device, and it’s unclear whether their approach would scale up to 6-DoF successfully.

[46] Sagardia, M., & Hulin, T. (2017, March). Evaluation of a penalty and a constraint-based haptic rendering algorithm with different haptic interfaces and stiffness values. In 2017 IEEE Virtual Reality (VR) (pp. 64-73). IEEE. https://doi.org/10.1109/VR.2017.7892232

Conclusion

In this paper, we proposed a review of haptic rendering techniques in the light of our application, total hip replacement surgery training. We described each technique with some details, and referred to previous usage in the domain of surgery simulation.

At this point of our study, none of the haptic rendering techniques offers a clear answer to our objectives. Therefore, our intention is to proceed with implementing each of them, and their combinations, inside a simple test environment representative of the tasks to be carried out by the trainees. Then, we intend to perform a user study of the face validity of the different approaches.

Acknowledgements

This paper is a result of the research carried out within the project "DynamicHIPS". The research project "DynamicHIPS" is funded by the German Federal Ministry of Education and Research (BMBF).

SPONSORED BY THE

Federal Ministry of Education and Research