Low-end haptic devices for knee bone drilling in a serious game

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Abstract

Purpose – The purpose of this paper is to examine the application of low-end, low-fidelity (gaming/consumer-level) haptic devices for medical-based, surgical skills development (surgical bone-based drilling in particular) with serious games and virtual simulations as an affordable training solution with the potential of complementing current and traditional training methods.

Design/methodology/approach – The authors present the adaptation of two low-end haptic devices (Novint Falcon and Geomagic 3D Touch) to simulate a surgical drill drilling through bone for a serious game developed for total knee arthroplasty training. The implementation was possible through the analysis of the bone drilling mechanics. The authors provide a quantitative comparison of both haptic devices with respect to forces, movements, and development.

Findings – Although further testing is required, the initial results demonstrate that the low-end, consumer-level haptic devices can be incorporated into virtual environments/serious games to allow for the simulation of surgical drilling. The authors also believe that the results will generalize and allow these devices to be used to simulate a variety of technical-based medical procedures.

Originality/value – In contrast to previous work where the focus is placed on cost-prohibitive haptic devices, this approach considers affordable consumer-level solutions that can be easily incorporated into a variety of serious games and virtual simulations. This holds promise that haptic-based virtual simulation and serious games become more widespread, ultimately ensuring that medical trainees are better prepared before exposure to live patients.

Keywords Virtual simulation, Serious gaming, Haptic, Low fidelity

Paper type Research paper

1. Introduction

Total knee replacement or total knee arthroplasty (TKA) is a surgical procedure where part of the knee joint surfaces is replaced with metal and polyethylene counterparts that mimic the replaced cartilage bone (Scott and Insall, 2012). This is a common procedure with approximately 400,000 knee replacements performed annually in the USA alone (Manner, 2008), while 4.7 million were performed globally in 2010 (Maradit Kremers *et al.*, 2015). Manual drilling is a fundamental component of the TKA procedure. However, to properly operate the surgical drill, surgeons must possess great dexterity (to compensate for vibrations inherent with drilling, friction, and force), to achieve the desired depth without compromising the bone, all of which require an extensive amount of training and practice (Tsai *et al.*, 2007).

The field of simulation is currently seeing great effort and emphasis placed on the use of virtual reality (VR) and video game-based technologies including serious games (i.e. video games applied specifically to learning and training). Serious games provide a high level of interactivity and engagement not easily captured in traditional teaching/learning environments (Graafland *et al.*, 2012). Serious gaming and virtual simulation provide medical trainees the opportunity to acquire, practice, and maintain both non-technical skills

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(e.g. cognitive, communication, leadership) and technical skills outside of the medical environment in an interactive, engaging, and cost-effective manner. They allow trainees the opportunity to train until they reach a specific competency level, thus better preparing them before exposure to live patients. Gaming-based hardware and software have been used to address medical challenges with innovative solutions. For example, 3D displays have been applied to anatomy education (Hackett and Proctor, 2016), and haptic devices have been applied to surgical training (Nyström *et al.*, 2016), tissue palpation (McKinley *et al.*, 2015), and bone drilling (Wang *et al.*, 2015). Although the use of virtual simulation and serious gaming in medical education is rapidly becoming more widespread, most applications are still focussed on cognitive skill development. Due to various technical limitations and cost issues, technical skill development (including surgical drilling skills) in the virtual domain is still in its infancy, and when present restricted to larger institutions that can afford the associated complex and costly hardware, and haptic devices in particular. Although lower cost haptic devices are available, further studies are required to guarantee their suitability for medical training and as an alternative to costly solutions that may be unavailable to all training procedures and medical trainees across medical institutions (Tokuyasu *et al.*, 2014).

Our ongoing work is examining the use of low-end (gaming/consumer-level) haptic devices for medical-based, surgical (technical) skills development with serious games and virtual simulations as an affordable and cost-effective training solution. Within the scope of this paper, we are focussing on the drilling associated with the TKA procedure and aim to establish the suitability of low-end haptic devices for this purpose. We anticipate that our findings will span across other surgical domains. To this end, we present the adaptation of two low-end haptic devices (the Novint Falcon and the Geomagic 3D Touch) to a serious game for TKA training with an emphasis on surgical drilling. The haptic devices are used to simulate drilling through bone, accounting for the insertion and vibrations during the procedure. We provide a quantitative comparison of both haptic devices with respect to forces, movements, and overall development. Although greater work remains, our initial results indicate that low-end haptic devices can in fact be used to simulate a surgical drill and when incorporated into a serious game/virtual simulation can be used to support the development of surgical drilling.

2. Background

Haptic devices provide touch-based feedback and this can provide a greater sense of realism and immersion in virtual environments (Coles *et al.*, 2011). However, the use of haptic devices is constrained to hardware that can provide different variations of realism in terms of object interactions and ranges of movement (Burdea and Coiffet, 2003). A summary of various currently available haptic devices along with their features, characteristics, and cost is presented in Table I.

2.1 Haptic-based simulation

Prior work has seen the incorporation of haptic devices to support technical-based surgical skills development across various surgical procedures including minimally invasive surgical training (Basdogan *et al.*, 2004), laparoscopy (Basdogan *et al.*, 2001), organ interaction (Webster *et al.*, 2002), and orthodontics (Bakr *et al.*, 2012) amongst many others. Drilling is an important component of various surgical procedures. Morris *et al.* (2004) presented a framework for temporal bone surgery training, where bone removal is performed using a variety of drill heads called burrs. For haptic rendering, the burr is represented as a cloud of sample points evenly spread around the spherical surface of the burr. Massie and Salisbury (1994) employ volumetric data obtained from CT scans (X-ray computed tomography) to represent the bone and simulate the drilling process using a SensAble Phantom haptic device which includes three degrees of freedom (3DOF) for force feedback and six degrees of freedom (6DOF) for

Device/ feature	Falcon US $250	Touch 3D Stylus US $600	Geomagic Sculpt US $3,900	Geomagic Touch X US $30,000	Premium	Premium high force	Premium 3
Workspace	Translational 10.6 cm^3	Volumetric 16×12×7 cm	Same as touch	Same as touch	Volumetric 38.1×26.7×19.1 cm	Same as premium	Volumetric 83.8×58.4×40.6 cm
DOF	3	5	5	5	6	6	6
Force	8.9 N	3.3 N	3.3 N	7.9 N	8.5 N	37.5 N	22 N
Position resolution	400 dpi	450 dpi	450 dpi	1100 dpi	860 dpi	3784 dpi	1000 dpi
Stiffness	na	na	x 1.26 N/ mm	x 1.86 N/ mm	3.5 N/ mm	3.5 N/ mm	1 N/ mm
	na	na	y 2.31 N/ mm	y 2.35 N/ mm			
	na	na	z 1.02 N/ mm	z 1.48 N/ mm			

Notes: Games and consumers products Novint, Novint Falcon, www.novint.com/index.php/novintfalcon; 3D Systems, Touch 3D Stylus, www.3dsystems.com/shop/touch; Geomagic, Geomagic Touch, www.geomagic.com/en/products/phantom-omni/overview; Geomagic, Geomagic Touch X, www.geomagic.com/en/products/phantom-desktop/overview; Geomagic, Geomagic Premium, www.geomagic.com/en/products/phantom-premium/overview

Table I. Haptic device comparison

positional input. However, the voxel bone data used to generate the haptic feedback and to allow for the removal of bone material does not render realistically due to its limited resolution. Auditory feedback is also provided; the sound of the drill is frequency modulated based on both the amount of pressure that the user applies and the type and thickness of the material in contact with the burr.

Vankipuram *et al.* (2010) presented a virtual orthopaedic drilling simulator designed to provide a realistic training environment with visual and haptic feedback (they employed a SensAble Phantom haptic device). The haptic feedback is generated based on contact between a virtual drill bit and a low resolution voxelized bone created from CT scans. The visual representation of the bone is a triangulated mesh that is updated in real time using the marching cubes algorithm. The simulation also tracks and analyses the movements of the trainees to determine their surgical proficiency. Two user studies were conducted which compared the error rate of novice trainees to senior surgeons and residents. As expected, the error rate of surgeons was much lower than that of novice trainees although the error rate of novice trainees decreased with practice.

In orthopaedic surgery simulation, sensory stimuli have been mainly focussed on graphical rendering (e.g. collision detection, realism, deformable objects, animations, geometric modelling) (Peng *et al.*, 2003; Niu *et al.*, 2010) and force feedback using various methods, including the force model presented by Chi *et al.* (2005). In the force model of Chi *et al.* (2005), the position and orientation of the drill along the drilling trajectory provide haptic feedback while rendering the operation. Esen *et al.* (2004) described a method for bone drilling training that allows for 3DOF and conveys force, visual, and auditory feedback. A study conducted to examine the effectiveness of the method showed marked improvements and indicated that auditory cues can improve the drilling technique. Vankipuram *et al.* (2010) presented a visio-haptic simulation device to provide a realistic training environment for orthopaedic surgeons to practice with virtual bones. The device tracks user movements to determine surgical proficiency.

Although a number of virtual simulations have employed haptic devices including those focussed on bone-based drilling and orthopaedic surgery training, most approaches employ high-fidelity haptic devices that are costly and thus their use is not widespread. In contrast to previous work that has made extensive use of high-fidelity haptic devices, here we examine and compare the feasibility of two low-end (gaming/consumer-level) haptic devices for knee bone-based drilling simulation within a serious gaming environment.

3. Methods

The development process of our tool for knee bone drilling is comprised of three main stages: bone drilling mechanics required for the TKA procedure, implementation of the haptic feedback, and finally, VR and haptic integration. The following subsections outline each of the stages.

3.1 Bone drilling mechanics

A bone is composed of cortical and cancellous tissue (Gibson, 1985). As with any other material, the mechanical properties of the bone (e.g. modulus of elasticity, shear modulus of elasticity, and Poisson's ratio), determine how it behaves under various conditions (e.g. impact, bending, drilling, etc.). Bone is a brittle material and it produces discontinuous chips that require increasing thrust force and torque while clogging (Wiggins and Malkin, 1976). While drilling, the drill bit may clog as a result of high spindle speeds and/or slow feed rates which can also lead to heating and this heating can ultimately lead to osteonecrosis (Augustin *et al.*, 2012).

The TKA procedure involves many activities including bone drilling of the femoral and tibia bones, an activity that requires dexterity skills, teamwork, and knowledge regarding the mechanical behaviours surrounding the procedure. To perform the drilling operation, the surgeon aligns the drill bit with the desired point of insertion marked to help guide the bit into the bone. To reach the target drilling depth, the surgeon is required to estimate the adequate spindle speed to avoid excessive heat that can harm the bone and cause various health-related issues (Pandey and Panda, 2013). Various studies related to bone drilling have provided an understanding of how the insertion and extraction drilling mechanics work, with respect to time, forces, and spindle speeds for each bone tissue layer (MacAvelia *et al.*, 2012).

To implement the bone drilling scenario with the haptic devices, we first identified the parameters required to represent the drilling process and identified what limitations the haptic devices and associated libraries pose to ensure that the model and interactions can be adjusted. We employ the drilling thrust force model proposed by MacAvelia *et al.* (2012), which they developed through a series of experiments conducted with numerical controlled machines and bovine bones whose mechanical properties are similar to human bones (Allotta *et al.*, 1997), and a drill bit used in orthopaedic surgery (stainless steel bit, with 2.7 mm diameter and a length between 130 mm) (Chi *et al.*, 2005). From the thrust force and torque experimentation within a 6DOF scenario with various misalignments, MacAvelia *et al.* (2012) determined that the optimal drilling conditions require fixed values for drill feed rate and spindle speed of 1.5 mm/s and 1,500 rpm.

3.2 Implementation

To implement the virtual drilling scenario, the mechanical behaviour of the drill is required as it provides the information to achieve suitable haptic interactions. Our implementation presents the user with an environment whereby drilling through the cortical and cancellous bones is possible. The user can perform the drilling according to literature findings, where drilling occurs at spindle speed of 1,500 rpm, thus resulting in a variety of haptic and sound feedback while drilling through the bone. An overview of the proposed system architecture is provided in Figure 1. As illustrated, the user inputs are transmitted to the virtual drilling system (through the corresponding plugins), which ultimately triggers the force model in the virtual environment that provides visual, audio, and haptic feedback during the drilling process.

We chose to implement our bone drilling model with two low-end, consumer-level haptic devices, the Novint Falcon and the Geomagic 3D Touch (see Table I for a summary of their technical characteristics). The Novint Falcon (see Figure 2(a)) is a 3DOF haptic device used as a user interface (UI) for games. It has also been used in medical-based training scenarios

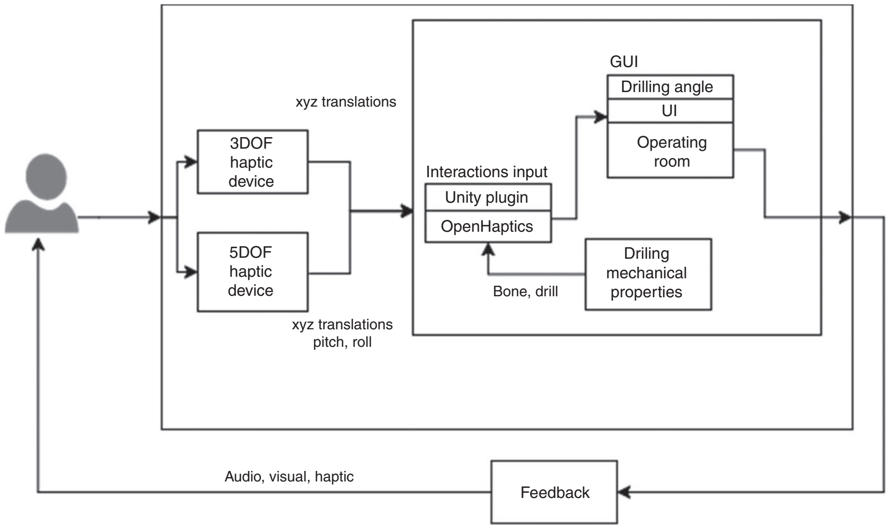
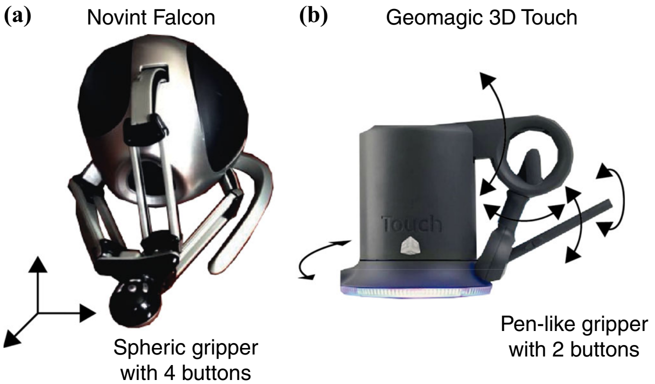


Figure 1.
System architecture



Note: The arrows represent the number of degrees of freedom (DOF) of each device

Figure 2.
Haptic devices

(e.g. dental training simulation (Tse *et al.*, 2010)). The manufacturer provides an SDK and various free videogame plugins. The SDK allows developers to develop custom applications to interact with the Novint Falcon through C++ programming interface. Also available is the falconunity library[1] that allows interfacing the Novint Falcon with the Unity3D game engine. The library provides support to implement both rigid bodies and spring rigid bodies.

The Geomagic 3D Touch (see Figure 2(b)) is a low-end, plug and play haptic device with 5DOF that allows for realistic movements (Silva *et al.*, 2009). It includes pre-programmed software that provides haptic rendering capabilities. This device is designed for, and targeted to 3D content creators and sculptors[2], but its capabilities allow for a variety of other uses. Also available is the OpenHaptic Unity3D game engine plugin[3] which enables modification of different haptic parameters such as friction, shape, texture, roughness, stiffness, and damping. The OpenHaptic API is based on the C++ programing language and allows the implementation of custom-made haptic interactions into simulations, games, or 3D modelling software (Itkowitz *et al.*, 2005).

3.2.1 The virtual environment integration. The 3D virtual operating room (see Figure 3) developed by Cowan *et al.* (2010) as part of a serious game for TKA training (i.e. the TKA serious game), was used here (suitably modified to allow for the haptic integration). In the TKA serious game, trainees begin the in the operating room taking on the role of the orthopaedic surgeon, viewing the scene in a first-person perspective. The world is viewed through the viewpoint of the trainee's avatar and as such, the avatar's body is not viewed (except for their hand). Several other non-player characters (NPCs) also appear in the scene including the patient (lying on a bed), assistants, and nurses. The trainee can move and rotate the "camera" using the mouse in a first-person style, thus allowing them to move within the scene. A cursor appears on the screen and the trainee can use this to point at specific objects and locations in the scene. The goal of the game is to go through each step of the TKA procedure and at each step, choose the appropriate tool(s) required to complete the corresponding step. Once the tool for a step has been chosen, a menu appears providing the trainee a list of options corresponding to that step. Once the correct option is chosen, the trainees are asked a multiple-choice question to test their knowledge of that step. Answering correctly results in several "points" earned which are added to an accumulating score. If the trainees answer the multiple-choice question incorrectly, they are corrected via text and/or illustrations (in a pop-up window). If the trainees choose an incorrect tool(s) for the corresponding step or perform a step out of order, they are also corrected through a text description often accompanied by a diagram of the procedure. When the procedure is complete, the trainees are shown a "score card" providing them feedback regarding their performance.

The haptic devices were integrated into the TKA serious game environment using the Unity 3D[4] game engine. The procedure was limited to the drilling and kept the same first-person perspective.

3.2.2 Development of the virtual bone models. To achieve a realistic bone drilling simulation the following is required (Coles *et al.*, 2011): a proper mechanical model of the bone, a proper mechanical model of the drill, a proper computer graphics visualization, and finally, a haptic device capable of reproducing accurate drilling-based interactions. Since each haptic device is constrained by its available libraries/plugins, two distinct groups of bones were modelled to provide the best experience with each UI. With respect to the Geomagic 3D Touch device, the bone model is comprised of four layers (four closed bone geometries, one within the other), configured to provide haptic feedback resembling the

Figure 3.
Sample screenshot of the virtual operating room from the TKA serious game of Cowan *et al.* (2010)

cortical and cancellous bones (see Figure 4). The virtual drill bit is configured to interact with the bone layers in a realistic manner using as reference the drilling mechanical properties (MacAvelia *et al.*, 2012). To accomplish this, the Geomagic 3D Touch OpenHaptic plugin was configured with the stiffness, damping, friction, and percentage of penetration (POP; a parameter configured to move from one layer to the next, depending on the thickness of each layer) parameters presented in Table II.

Similarly, the Novint Falcon required a suitable bone model to provide drilling interactions. After analysing the falconunity library, we identified that it was not possible to implement material insertions as the interactions were limited to outer rigid body collisions with adjustable parameters regarding the material properties and interactions through a mass-spring script. To address this shortcoming, the bone layer models used with the Novint Falcon were hollow with the point of insertion marked so drilling interactions can occur once the drill bit collides with two geometries, configured to provide haptic feedback during the drilling trajectory. Since the drill bit goes through the cortical and cancellous bone layers, we used the bone thickness and the time that it takes to go through the bone to provide proper haptic feedback resembling real world drilling and progression (MacAvelia *et al.*, 2012; Treece *et al.*, 2010). This, in conjunction with the system properties presented in Table III, allowed us to calculate the thrust forces using the libfalcon library's mass-spring model based on damping presented in Figure 5. However, it is worth noting that given the porous properties of the cancellous bone, the force required through it is minimum (thickness between the trabecular bone structure is in the order of microns) (Parkinson and Fazzalari, 2013), and the most important aspects are the depth, drilling speed, and drill orientation; hence there is no cancellous bone and drilling time specified.

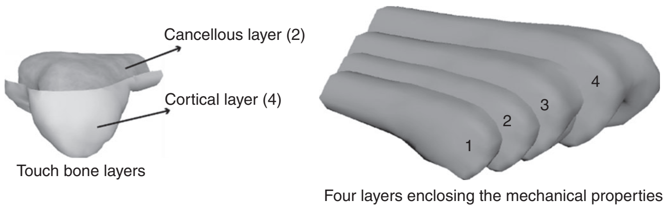


Figure 4. Bone layers used to obtain haptic drilling feedback with the Geomagic 3D Touch

Table II. Mechanical properties for the bone layers with the Geomagic 3D Touch haptic device

Layer	Stiffness and tangential stiffness	Damping and tangential damping	POP	Static and dynamic friction
1	1	0.8	0.1	0.3
2			0.3	0.6
3			0.5	0.8
4			0.8	1

Table III. Novint Falcon falconunity mass-spring settings

Bone/property	Thickness	Drilling time	Force	Damping coefficient
Cortical	4 mm (Treece *et al.*, 2010)	5 s (MacAvelia *et al.*, 2012)	3 N (MacAvelia *et al.*, 2012)	3.75 Ns/mm
Cancellous	na	na	0.5 N (MacAvelia *et al.*, 2012)	na

3.3 Integrating the haptic devices into the TKA serious game

The integration process requires the attachment and configuration of C# scripts to the virtual objects to guarantee proper drilling behaviours from a software standpoint, and the hardware adjustment for the devices to convey a proper haptic experience. To provide greater realism, a pair of custom drilling handles were designed, 3D printed, and attached to the haptic devices (see Figures 6 and 7), to avoid discomfort and reduced immersion from using the default end effectors of the Geomagic 3D Touch and Novint Falcon devices (shown in Figure 2). Since the movements are constraint by the haptic devices' workspace, the game camera was fixed on the knee of the virtual patient.

The trainee is required to drill through the cortical and cancellous bones to a certain depth. When the trainee activates the drill, a drilling sound is reproduced and once the drilling starts, the sound, vibration, and drill bit speed change according to the cortical bone drilling mechanics. During drilling, the trainee's movements and angles are monitored by comparing them with an ideal trajectory set up to reach the goal as presented in Figure 8. Random sounds are produced to simulate equipment failure scenarios that the trainee is required to identify. Since the chosen haptic devices have different DOFs, their setup differs. Furthermore, rotations with the Novint Falcon cannot be achieved.

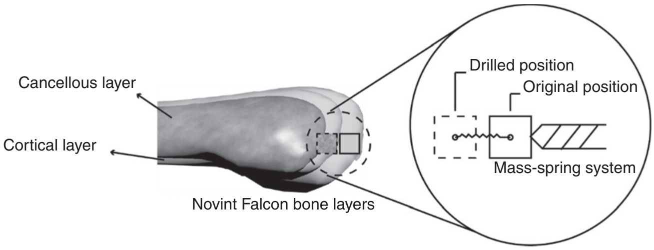


Figure 5.
Mass-spring model used to obtain haptic drilling feedback with the Novint Falcon

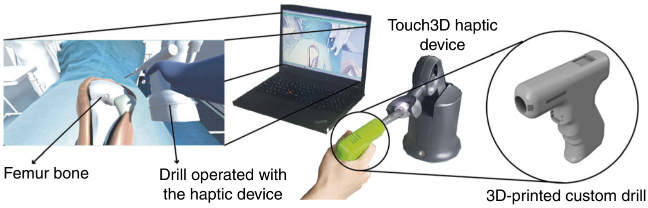


Figure 6.
Custom-designed and 3D-printed drilling handle for the Geomagic 3D Touch haptic device

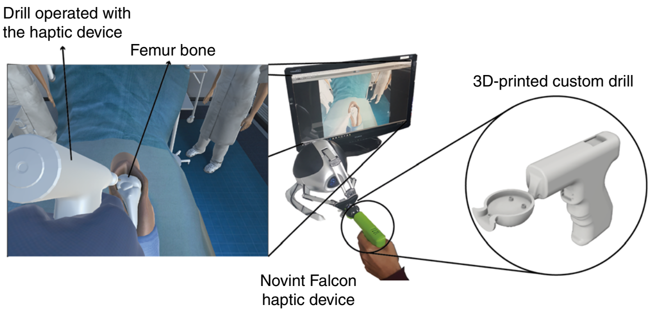


Figure 7.
Custom-designed and 3D-printed drilling handle for the Novint Falcon haptic device

4. Experimental results: comparing the two haptic devices

To compare how the haptic feedback matches the theoretical model, we configured the Geomagic 3D Touch and the Novint Falcon plugins to respond to cortical and cancellous thrust forces during drilling with the layered bone model and the mass-spring model, respectively, as described in Section 3. According to MacAvelia *et al.* (2012), the thrust force required to drill through the cortical bone is approximately 5.6 N, diminishing to 0.5 N once it reaches the cancellous bone. Our implementation with the Geomagic 3D Touch provided a force of 3.3 N (the maximum available force generated with the device; see Table I) for the cortical bone and a force of 0.5 N for the cancellous bone. With respect to the Novint Falcon, both forces were obtained in accordance with the theoretical model.

Additionally, we maintain a record of the pitch angle and the penetration ratio (current drill bit penetration distance divided by the maximum penetration distance) to let the trainee know the position of the drill bit within the bone. Figure 9 presents a sample of the captured data during three drilling attempts, where it can be seen that the drilling angle varies depending on the depth. More specifically, the deeper the drill bit goes (Figure 9(a)), the fewer pitch variations the user experience (Figure 9(b)); this is similar to drilling in the real world.

With respect to the Novint Falcon, given the limitations (movement constraints) associated with the device, the user movements were not monitored as the drill bit can only follow one predefined trajectory to represent the haptic interaction and cannot exceed the force applied to drill through the bone.

5. Discussion/concluding remarks

In this paper, we described an approach to allow the inclusion of low-end, consumer-level haptic devices (the Geomagic 3D Touch and the Novint Falcon), into a serious game for total knee arthroplasty (TKA) training to allow for the simulation of a surgical drill which is an integral component of the TKA procedure. We also provided a comparison of both devices with respect to the required forces and movements inherent with surgical drilling through the bone.

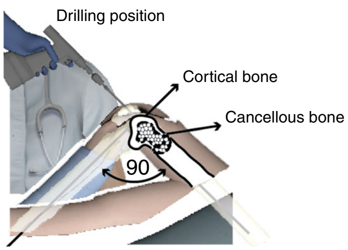


Figure 8. Drilling angle and trajectory

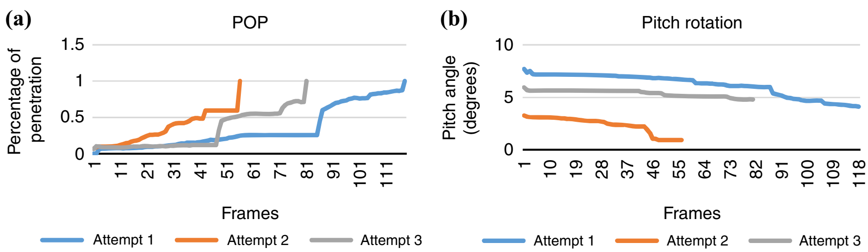


Figure 9. Captured drilling data for the Geomagic 3D Touch

The haptic environment for the Geomagic 3D Touch was developed using the OpenHaptic Unity Plugin which presents several limitations compared to the actual bone model. More specifically, it is not possible to model torque/rotation with the plugin which is an important characteristic of any drilling procedure. In addition, the required (actual) experimental force far exceeds the maximum force that can be produced by the Geomagic 3D Touch device. The plugin does not provide the ability to programme custom-made forces that would allow for the creation of richer haptic interactions for the simulation. However, these limitations are compensated with the ability to change the haptic parameters during run-time to quickly determine the best parameters that model after bone interactions.

With respect to the Novint Falcon, the haptic interactions using the Unity3D game engine falconunity library were limited to rigid bodies and mass-spring rigid bodies. Given this limitation, haptic movement through the 3D objects was not possible and force over exertion may damage the device if it exceeds the actuator's limit (Table I), whereas the OpenHaptic library does allow a configurable threshold for the haptic object to pass through the 3D object, which results in more realistic interactions and possible applications in needle insertion simulation. Another limitation we observed regarding the rigid body physics of the falconunity library was related to the interactions between the drill bit and the hole, given that the tolerance required between the diameter of the hole and the diameter of the drill bit must be greater than 10 per cent for the drill to go through the hole. This situation was addressed by limiting the axis movement of the drill bit. Finally, since the Novint Falcon must be calibrated every time the game runs, there is the possibility that the drill is rendered inside another object, in which the game has to be restarted. This occurs as a result of the reconnection of the device with the SDK via the server. Even though the plugin presents these limitations, it was possible to customize the plugin with the reference model to provide a thrust force equivalent to the theoretical one. The use of 3D printing provided customization that can be improved in the future by adding greater futures including wireless communication, buttons, and additional degrees of freedom.

In both cases, the ease of access to the Unity3D game engine also enabled the ability to utilize Unity3D's powerful tools to develop the graphical environment and interface that guide the user through the training procedure. Although the Unity3D game engine allowed us to rapidly prototype the environment and the limited haptic interactions, we believe that further work using OpenGL with the devices SDK can provide more accurate interactions and flexibility to better represent the drilling process.

Although further testing is required, our initial results demonstrate that the low-end, consumer-level haptic devices can be incorporated into virtual environments/serious games to allow for the simulation of surgical drilling. We also believe that our results will generalize and allow these devices to be used to simulate a variety of technical-based medical procedures. Future work will involve further refinement of the bone drilling model for both haptic devices followed by the assessment testing of the models with orthopaedic surgeons/residents.

Notes

1. FalconUnity library, https://github.com/kbogert/falconunity
2. 3D Systems, Touch 3D Stylus, www.3dsystems.com/shop/touch
3. Unity Haptic Plugin for Geomagic OpenHaptics, www.assetstore.unity3d.com/en/#!/content/19580
4. Unity3D, http://unity3d.com/

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