CREATION OF TRAINING MODELS FOR ESTABLISHING INTRAOSSEOUS ACCESS WITH USE OF 3D PRINT – FOLLOWING STUDY

Tvorba modelů pro trénink zavedení intraoseálního vstupu – navazující studie

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Abstract

3D printing technology and simulation medicine have been both experiencing big boom recently. In this work we would like to demonstrate process of creation of training task models for establishing intraosseous access at several locations.

We used 3D scanner and anatomical preparations (humerus and tibia) for creation of the models in the form of .stl file. The models were 3D printed. Students´ feedback was assessed with use of structured questionnaire.

Anatomical structures that are necessary for identification of the place of establishing intraosseous access are well-palpable in all models. When part of each model simulating cortical layer of bone was drilled through a significant feeling of give appeared as a sign of entrance into trabecular part of the bone. Several physicians working either in the field of emergency or anesthesiology confirmed fidelity of our models. Most of the students (88.97 %) reported that our models correspond better to real bones when compared to commercially available models.

The models we created are realistic, easy to reproduce and very cheap. Simulation medicine and medical education may benefit from use of 3D printing technology.

Key words: *simulation medicine, 3D print, intraosseous access, benefit, students*

Introduction

Simulation, in its many guises, is now widespread in many fields of human endeavor and its history stretches back over centuries (Bradley, 2006). For example, the first flight trainer named "Blue Box" was developed by Edwin Link in 1929 (Rosen, 2008). Even though the history of simulation medicine dates back into ancient times (Meller, 1997), the real boom of simulation-based medical education (SBME) developed just over several past decades (McGaghie, Issenberg, Petrusa & Scalese, 2010). The variety of medical simulators ranges from simple task trainers (e.g. suturing, inserting an endotracheal tube, establishing intraosseous access etc.) to highly sophisticated mannequins which provide a possibility of simulating fidelitous clinical scenarios such as myocardial infarction, stroke, pneumothorax etc. (Kunkler, 2006; Sova et al., 2019)

Vascular access is of paramount importance in the care of critically ill patient (Luck, Haines, & Mull, 2010). Obtaining emergency intravascular access in critically ill (especially pediatric) patients can be extremely difficult, time consuming, and at times impossible since the peripheral veins are often collapsed, central lines carry risks, and cutdowns can take considerable amount of time (Anson, 2014; Rosetti, Thompson, Miller, Mateer, & Aprahamian, 1985). On the other hand, vessels in red bone marrow do not collapse during shock (Orlowski, Porembka, Gallagher, Lockrem & VanLente, 1990). Drinker, Drinker, & Lund (1922) and Doan (1922) were the first to independently reveal that bone marrow may serve as a transfusion route. The technique was used frequently during World War II and experienced decrease in its use afterwards (Heinild, Sondergaard, & Tudvad, 1947; Fiser, 1990). Its renaissance started in 1980s (Anson, 2014; Fiser, 1990). There have been several studies conducted on comparison of pharmacokinetics and effectiveness in establishment of intravenous and intraosseous access. These studies confirmed that intraosseous access is at least as beneficial as intravenous access, maybe even better (Johnson et al., 2015; Lewis & Wright, 2015; Reades, Studnek, Vandeventer, & Garrett, 2011; Von Hoff, Kuhn, Burris, & Miller, 2008). Nowadays, intraosseous access is an approved alternative route of administration of drugs included in resuscitation guidelines. It is efficiently used for administration of drugs in advanced life support of both pediatric (Maconochie et al., 2015) and adult (Soar et al., 2015) patients until central venous catheter is inserted (Buck, Wiggins, & Sesler, 2007; Hoskins, do Nascimento Jr, Lima, Espana-Tenorio, & Kramer, 2012).

Vast amount of work has been done in the field of 3D printing since Charles W. Hull (Hull, 1986) patented the first stereolitograph – a predecessor of modern 3D printers. In the past years, 3D printers became cheap and widespread. 3D printing is a rapidly expanding method of manufacturing that already found numerous applications in healthcare, automotive, aerospace and defense industries and in many other areas (Berman, 2012, Dodziuk, 2016). There is a wide range of applications in medicine including dentistry, tissue engineering and regenerative medicine, engineered tissue models, medical devices, anatomical models and drug formulation (Liaw & Guvendiren, 2017; Shafiee & Atala 2016; Tack, Victor, Gemmel, & Annemans; 2016).

In our previous study we tested the possibility of making a simple model of proximal tibia for training of establishing intraosseous access with use of 3D printing technology (Snehota, Kikalova, Kapral, Vachutka, & Plhak, 2019). The model we created was realistic, cheap and easily reproducible. Therefore, we decided to carry on and further improve our model, create models of other places that are typical for establishment of intraosseous access and present the models to students.

Aim

The main goal of this work is to further significantly extend our previous study. In this work we identify proper hardness of the model, create more anatomically accurate medullar cavity, design models of other places that are typical for establishment of intraosseous access and we also conduct a study monitoring students´ response to our and commercially available models when compared to real bones.

Methods

Anatomical preparation

Bones from the collection of the Department of Anatomy of the Faculty of Medicine and Dentistry of the Palacký University in Olomouc were used as models for 3D scanning. The bones in the collection of the Department of Anatomy come from donors who gave a written consent to provide their bodies for teaching and research purposes of students and researchers. At the end of the topographic-anatomical autopsy, which is part of general medical education, the bones were prepared using wet preparation technique. Firstly, we put the bones into boiling water. Then we used sharp tools to remove soft tissue. Subsequently we dried the bones. Lastly, the bones were marked and properly recorded. The bones come from 3 different cadavers. Bone preparation is a time and mentally demanding task and is performed by autopsy technicians.

Hardness of the model

To approach ideal hardness of the material of models (hard enough to remind of the hardness of the bone and provide a feeling of a give when drilling through the cortical layer) several small testing cubes were created. A 1x1x1 cm cube was designed using www.tinkercad.com (Autodesk, San Rafael, California, USA) and exported in .stl format. Using Slic3r software (Prusa Research, Prague, Czech Republic) .gcode files of cubes of different densities of cubic infill were created. The printing was performed with the same equipment, parameters and under the same conditions as the final models of bones described below. Then, an intraosseous drill EZ-IO® G3 and intraosseous needle EZ-IO® 25 mm 15 ga (Teleflex Incorporated, Wayne, Pennsylvania, USA) were used to test the hardness of cubes. We asked the head physician of Centre for Emergency Medicine in University Hospital Olomouc to test infill densities of 50 – 100% with 10% step and determine which one is closest to real situation. Densities below 50% were too soft. Testing of the hardness of cubes was blinded for the head physician.

3D scan

The bones were scanned using a desktop 3D scanner 3D EinScan-SE (Shining 3D, Hangzhou, China) based on structured light technology. The software used to operate the scanner was EinScan-SE series_v2.7.0.8 (Shining 3D, Hangzhou, China). The scanner was calibrated using a procedure recommended by the manufacturer prior to scanning of the bones. Dual-camera HDR regime involving a turntable (15° steps) was used to scan each bone from different angles. Moreover, after the scanning cycle was finished each bone was repositioned twice to scan parts which could not be captured previously. After each repositioning the bone was scanned again using dual-camera HDR regime involving a turntable (15° steps). After finishing the scan, a high detailed water-tight model was created and exported in the .stl format. Simplification ratio was used to encode the object with use of less than 250000 triangles which is a limit for uploading .stl file to online environment for creation and adjustment of 3D objects www.tinkercad.com (Autodesk, San Rafael, California, USA). No significant visual change of the model was observed after applying the simplification ratio. We scanned proximal part of left humerus, proximal part of left tibia and distal part of left tibia.

Adjustment of the model

Anatomical preparations of tibia and humerus were cut lengthwise to visualize trabecular (medullar) part of the bone. The cavity corresponding to trabecular part of the bone was created in each of our models. In Blender (Blender, Amsterdam, Netherlands) we used lattice deformation technique and smoothening, scraping and flattening functions to sculpt the shape of cavity corresponding to medullar cavity. Consequently, Boolean operators, rotation and slight scaling functions were used to optimize the model for printing purposes in www.tinkercad.com (Autodesk, San Rafael, California, USA). Then, the model was exported in the .stl format and transferred to Slic3r software (Prusa Research, Prague, Czech Republic) to create .gcode file containing printing information. A pre-set for printing from PLA material was selected (extruder temperature was set to 215 °C, bed temperature was set to 60 °C and layer height was set to 0.15 mm). Speed of printing was reduced to 80%. Supports were auto-generated only from the printer bed.

Models of soft tissues

Models of soft tissues were created using www.tinkercad.com (Autodesk, San Rafael, California, USA). Boolean operators and previously acquired .stl files of the bones were used to model soft tissue of the desired region. Consequently, Blender (Blender, Amsterdam, Netherlands) software was used to smoothen the surface of the models of soft tissue. Then, the models were exported in the .stl format and transferred to Slic3r software to create .gcode file. A pre-set for printing from FLEX material was selected (extruder temperature was set to 240 °C, bed temperature was set to 50 °C and layer height was set to 0.15 mm). No supports were generated. 0% infill was used in case of the model of tibia at both regions (proximal and distal) since the thickness of soft tissue in these regions is small and use of any infill density resulted in significant increase in toughness of the model. 25% concentric infill was used in case of the model of humerus since the thickness of soft tissue at this region is bigger (especially due to presence of deltoid muscle) when compared to previous ones. The model presented with suitable flexibility when this infill was used.

3D print and creation of the models

Each model of the bone was printed using FDM (= fused deposition modelling) 3D printer Original Prusa i3 MK3 (Prusa Research, Prague, Czech Republic) and PLA plastic filament for 3D printers, 1.75 mm diameter, white colour (Gembird, Almere, Netherlands). Each model of soft tissue was printed using 3D printer Original Prusa i3 MK3 (Prusa Research, Prague, Czech Republic) and Flexfill 98A* filament for 3D printers, 1.75 mm diameter, powder beige (Prusa Research, Prague, Czech Republic). Speed of printing was reduced to 80% in both cases. Models of the bones and corresponding soft tissue were glued together using Mamut glue (Den Braven, Oosterhout, Netherlands).

Comparison of our and commercially available models with real bones by students and statistical analysis

In order to evaluate students´ response to using the models for training of intraosseous access, we introduced a structured questionnaire to 145 students of 5th year of General Medicine. All students completed the survey at voluntary basis. For purposes of the survey, the models were anonymized and labelled as models A – our 3D printed models – and models B – commercially available EZ IO training bone models (Teleflex Incorporated, Wayne, Pennsylvania, USA). We compared 3 parameters of our models and commercially available models: palpation for identification of proper position of intraosseous drill, hardness of the models and feeling of a give as a sign of entering into medullar cavity in comparison to corresponding real formalin-fixed bone without soft tissue. All students tried out corresponding models A, B and real bone. The questions and possible answers are available in Table 1 together with obtained results. The results were statistically analyzed by chi-square test at level of significance $P < 0.05$. All calculations were performed by GraphPad Prism 6.0 software (GraphPad, San Diego, California, USA). Moreover, we asked students if they considered the models for training of establishment of intraosseous access for application of drugs useful and which models (our 3D printed models or commercially available models) they preferred in general. We also added a question: "Do you have any other comments or suggestions?" with free answer to the questionnaire.

Results

Density of 60% of cubic infill was determined by the head physician to be optimal for creation of the models. This density provided suitable hardness and sufficient feeling of the give when drilling through the cortical layer of the models.

Fig 1. Anatomical preparations which were 3D scanned: a) proximal humerus, b) tibia (proximal part was scanned) and c) distal tibia.

Figure 1 displays the anatomical preparations which were 3D scanned.

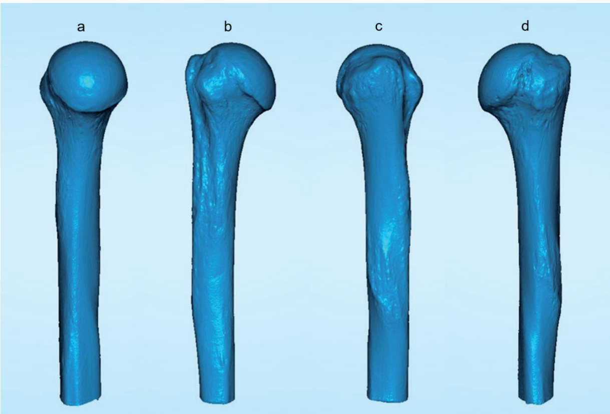

Fig 2. Different points of view of a model created from 3D scan of humerus: a) medial, b) ventral, c) lateral and d) dorsal.

Figure 2 shows water-tight model created from scan of proximal humerus from different points of view.

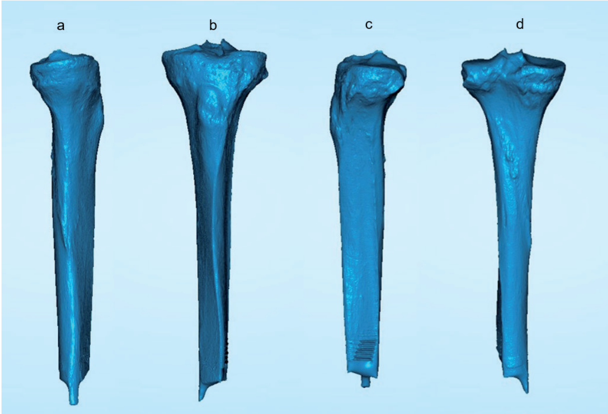

Fig 3. Different points of view of a model created from 3D scan of proximal tibia: a) medial, b) ventral, c) lateral and d) dorsal.

Figure 3 shows water-tight model created from scan of proximal tibia from different points of view.

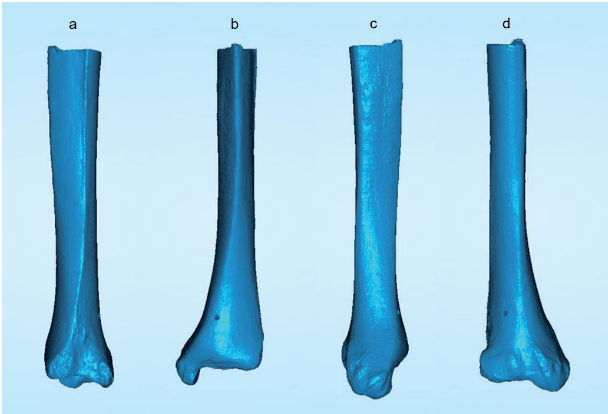

Fig 4. Different points of view of a model created from 3D scan of distal tibia: a) lateral, b) ventral, c) medial and d) dorsal.

Figure 4 shows water-tight model created from scan of distal tibia from different points of view.

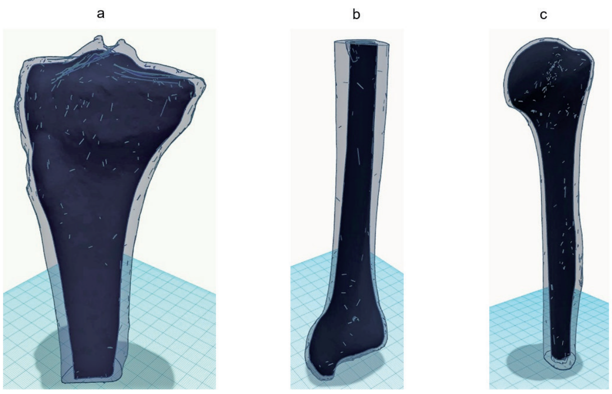

Fig 5. Representations of the cavities created using Blender and www.tinkercad.com. Solid parts of the models are transparent, black parts correspond to the cavities: a) distal tibia, b) proximal tibia and c) proximal humerus.

Figure 5 shows the models of the bones created using www.tinkercad.com. Solid parts of the models are transparent. Black parts correspond to the cavities representing medullar cavity and trabecular part of particular bones. When entering the black parts with the drill a significant give was felt in all cases. All models were mirrored to create the models of bones of contralateral side since right-handed people are in majority in the population and it is better to hold the models in left hand and intraosseous drill in right hand. Moreover, the models of proximal tibia and of proximal humerus were turned upside down as this configuration is spatially more suitable for 3D printing.

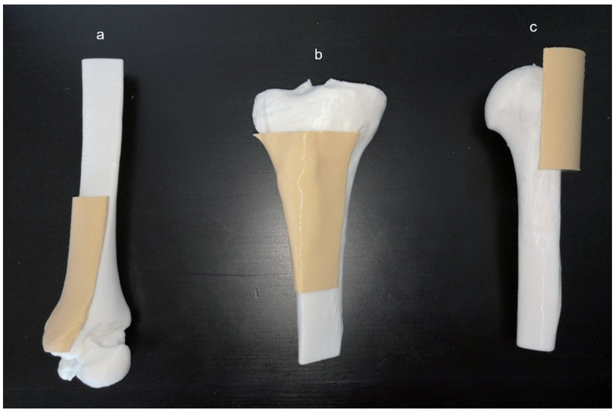

Fig 6. Final models for training of intraosseous access: a) distal tibia (with talus), b) proximal tibia and c) proximal humerus.

Figure 6 shows final models for training of intraosseous access.

Students´ feedback to the models

Vast majority of students (136/142 (95.77%)) generally considered the models for training of establishment of intraosseous access for application of drugs to be useful. The evaluation of selected parameters of our and commercially available models with comparison to corresponding real bones is summarized in contingency table (see Table 1). Statistically more students preferred our models in terms of palpability of anatomical structures which are necessary for proper identification of the position of the drill (P = 0.0011). Moreover, according to students´ responses, the hardness of our models as well as the felling of give as a sign of entering into medullar cavity in comparison to commercially available models were significantly closer to corresponding real bones (P < 0.0001 for both parameters). Finally, most of the students who answered question: "Which of the two models is better for training of establishment of intraosseous access for application of drugs?" (121/136 (88.97%)) preferred our models over commercially available models.

Table 1: *Comparison of parameters of our and commercially available models according to students´ opinion. Results show numbers (and percentage) of obtained answers for particular questions.*

		models created by 3D printer	commercially available models	statistical significance
How well do you feel anatomical structures necessary for identification of proper position of intraosseous drill during palpation?	I feel the structures very well.	102 (70.34%)	74 (51.75%)	*** P = 0.0011
	I am not sure I found particular anatomical structures.	43 (29.66%)	64 (44.76%)	
	I did not find anatomical structures.	0 (0.00%)	5 (3.50%)	
How hard are the models when compared to real bones?	The models are comparable to real bone.	82 (56.5 %)	25 (17.36%)	**** P < 0.0001
	The models are slightly softer.	55 (38.73%)	61 (42.36%)	
	The models are significantly softer.	5 (3.52%)	58 (40.28%)	
How significant is the feeling of give when drilling through the cortical layer (as a sign of entering into medullar cavity) of models when compared to real bones?	The feeling of give is significant.	111 (77.08%)	78 (53.79%)	**** P < 0.0001
	The feeling of give is not significant that much.	33 (22.92%)	55 (38.73%)	
	I did not feel the give.	0 (0.00%)	12 (8.28%)	

20 students left a commentary in the last question ("Do you have any other comments or suggestions?"). 10 students emphasized that our models correspond better to real bone in terms of hardness and feeling of a give. 7 students pointed out that our models of soft tissue should be more realistic and thicker. On the other hand, statistically more students preferred our models in terms of palpability of anatomical structures (see Table 1). 3 students praised us for the activity.

Discussion

Simulation medicine has experienced big boom in the past few decades. It provides students with the possibility of training and practicing skills which are usually highly specific and the possibility of their safe training in the hospital is limited. In case of complicated and specific procedures it is good to practice the procedure prior to performing it directly in a living patient. Thus, unwanted harm can be reduced. Makary & Daniel (2016) estimated that medical error (defined as unintended act or one that does not achieve its intended outcome, the failure of a planned action to be completed as intended, the use of a wrong plan to achieve an aim, or a deviation from the process of care that may or may not cause harm to the patient) is the third biggest cause of death in the US. Not all of the iatrogenic harm can be absolutely eliminated and in certain situations the physician has to consider the risk/benefit ratio (e.g. in case of side effects of drugs or use of imaging techniques based on ionizing radiation). However, using models and simulators prior to acquiring skills in clinical environment may prevent some of the harm (Ziv, Wolpe, Small, & Glick, 2003). In our humble view the simulation medicine is not meant to replace clinically acquired skills. We rather identify with the opinion that the role of simulation medicine is to serve as a valuable bridge between theoretical knowledge and real situations and clinical skills acquired in the hospital (Akaike et al., 2012; Susan Galloway, 2009; Morgan, Cleave-Hogg, Desousa, & Lam-McCulloch, 2006). Simulation based medical education can be a valuable tool for better clinical practice. It provides a safe, controlled environment in which problem-based learning is developed and competences are practiced in high standards (Jones, Passos-Neto, & Braghiroli, 2015). A trainee can make mistakes and learn from them without the fear of harming the patient (Al-Elq, 2010).

Using 3D scanner, 3D printer and several software programs we have demonstrated that 3D printing technology can be used for creation of the models for medical education. All models presented with well-palpable anatomical structures which are necessary for identification of the proper position of intraosseous drill (and needle respectively) – humeral caput, tibial tuberosity, anteromedial face of the tibia and medial malleolus. Significant feeling of a give appeared when we drilled through the cortical layer of the models and entered the cavity simulating trabecular part of the bone.

We decided to print the models using PLA filament because we expect to use a few kilograms of filament each year. PLA filament is made of corn starch and thus, it is biodegradable (Jang, Shin, Lee, & Narayan, 2007; Sudesh & Iwata, 2008) and environmentally friendly (Nampoothiri, Nair, & John, 2010; Vink, Rabago, Glassner, & Gruber, 2003).

The models for training of intraosseous access we created are highly realistic and easy to reproduce. After creation of the .gcode file the reproduction of model is a question of pressing of a few buttons. Moreover, our models are very cheap. Material for production of any model presented in this work costs much less than commercial models. Indeed, the material used for production of our model of proximal tibia costs 9.8%, of distal tibia 6.5% and of humerus 10.4% of the price of commercially available model. Exact prices are displayed in Table 2. Establishing an intraosseous access is a procedure relatively easy to learn (Petitpas et al., 2016). A short training including a lecture and practical use of plastic model significantly increases success rate (Gazin et al., 2011). However, when educating vast amount of medical students use of such commercially available plastic models may become economically exhaustive. Traditional manufacturing methods are still cheaper for large scale production however, the cost of 3D printing is becoming competitive for smaller production runs (Schubert, Van Langeveld, & Donoso, 2014).

Table 2: Comparison of price of our and commercial model.

	3D printed model	Commercial model	Price 3D / price commercial
Model of proximal tibia	£ 2.54	£ 25.94	9.8%
Model of distal tibia	£ 1.52	£ 23.47	6.5%
Model of proximal humerus	£ 2.44	£ 23.47	10.4%

Another advantage additive manufacturing provides is the possibility of customizing of the models (for example scaling the models or mirroring the models to the models of contralateral side). Other research teams also report similar benefits of using 3D printing technology for creation of the models for medical education (Lichtenberger et al., 2018; McMenamin, Quayle, McHenry, & Adams, 2014).

There is a certain amount of literature describing undisputable advantages of the models created by 3D printer with monitoring of students´ opinion (Hochman et al., 2015; Lim, Loo, Goldie, Adams, & McMenamin, 2016). However, according to the best of our knowledge, the models presented in this work have not been 3D printed so far as well as students´ feedback to these models has not been monitored yet. The vast majority (95.77 %) of interviewed pregradual students of 5^{th} year of General Medicine agreed that using of the models for training intraosseous access is useful. In general, the majority of students (88.97 %) preferred our models. Moreover, according to students´ opinions, our models correspond better to real bones than commercially available model in all tested parameters (palpation for identification of proper position of intraosseous drill, hardness of the models and feeling of a give as a sign of entering into medullar cavity).

Students of General Medicine systematically encounter practical training of establishment of intraosseous access for the first time in the 5^{th} year of their studies. Therefore, we also presented the models to 3 skilled physicians working either in the field of emergency or anesthesiology and resuscitation. All 3 physicians confirmed that our models correspond to real situation well in all 3 characteristics of the models (palpability of anatomical structures, hardness and feeling of a give). They also confirmed that our models are suitable for training purpose. All 3 physicians preferred our models over commercial ones.

Limitations of the Study

Even though we used real anatomical preparations in this study the final model was 3D printed. Models of soft tissue are not made from any kind of biological material but from flexible plastic material. Thus, the perceptions during palpation and identification of proper anatomical structures inevitably differ from the real situation.

Also, we used one hardness of the model. However, in real patients bone hardness is rather Gaussian distributed than being just one specific. The interindividual variability of bone hardness is determined by age, sex, ethnicity, presence of diseases (e.g. osteoporosis) etc. Thus, the feeling of a give and pressure which needs to be applied to intraosseous drill will differ in different patients.

Since the students completed the survey at voluntary basis our study may be influenced by selection bias to certain degree. Thus, even though the sample size was sufficient, the data acquired may not completely reflect the overall opinion of all students from 5^{th} year.

Conclusion

Using 3D printing technology, we have created highly realistic models for training of intraosseous access which has been confirmed by students´ opinion. The cost of the models is negligible when compared to commercially available models. 3D printing technology has a potential to become valuable tool significantly enriching the field of simulation medicine.

Acknowledgements

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Souhrn

Hlavním cílem této práce bylo rozšířit naši původní práci (Sněhota, Kikalová, Kaprál, Vachutka, & Plhák, 2019), tzn. určit optimální tvrdost modelu, vytvořit modely pro trénink intraoseálního vstupu pro další lokalizace (distální tibie, proximální humerus) a zhodnotit reakci studentů na prezentované modely. Metodika byla obdobná předchozí studii. Byly naskenovány anatomické preparáty, tyto modely byly následně upraveny pomocí softwarů www.tinkercad.com a Blender, které byly použity

k vytvoření dutiny uvnitř modelů a modely byly následně vytištěny na 3D tiskárně. Reakce studentů byla zhodnocena pomocí strukturovaného dotazníku, kdy studenti porovnávali naše a komerčně dostupné modely s reálnými anatomickými preparáty. Na všech modelech byly hmatné anatomické struktury nezbytné pro správnou lokalizaci místa zavedení intraoseálního vstupu. Při prostupu intraoseální jehly do spongiózní části kosti byla u všech modelů citelná ztráta odporu. Dotazníkové šetření ukázalo, že statisticky významná část studentů preferuje naše modely oproti komerčním. Provedená studie ukazuje možné přínosy 3D tisku v oblasti vzdělávání studentů medicíny.

Klíčová slova: *simulační medicína, 3D tisk, intraoseální vstup*

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