METHODICAL DESIGN OF A 3D-PRINTABLE ORTHOSIS FOR THE LEFT HAND TO SUPPORT DOUBLE BASS PERCEPTIONAL TRAINING

D. Borstell*, N. Walker**, S. Kurz*

* Research Laboratory for Additive Manufacturing, Koblenz University of Applied Sciences, 56075 Koblenz, Germany
** School of Music, Ithaca College, Ithaca, NY 14850

Abstract

The evolution of Additive Manufacturing (AM) in the past decades has opened up its use to a wide range of new applications where conventional manufacturing methods dominated. Orthoses are medical devices, mostly used on legs or arms after injuries or surgery. Amongst other functions, they limit the possible movement of limbs or joints to prevent excessive movements or loads during remobilization. Their manufacturing process is predominantly manual and conventional using e.g. plaster casts and materials like foam, wood and textiles.

Playing the acoustic double bass requires precise positioning of the left hand fingers on the fingerboard. Perception of the finger spacing is very important for good intonation. Different educational approaches have therefore been made to kinesthetic and perceptional training. Miniaturization and low forces allow applying additive manufacturing technology to a previously conventional device leading to a new approach to design a perceptional training device for the left hand: an individually shaped orthosis, which is lightweight, low cost, and adjustable and which can be worn during instrument practice.

Introduction

It is the goal of any professional musician to play a piece of music on an instrument in such a way that the audience feels it is beautiful and is willing to pay money for the performance. To achieve this a playing technique of high quality is required. Technical studies and exercises are therefore part of any musical curriculum. Playing acoustic string instruments requires precise positioning and spacing (intonation) of the left hand fingers on a fretless fingerboard. Timing according to the beat of the music must also be perfect.

The size of the double bass in comparison to smaller string instruments (e.g. violoncello or violin) requires higher finger and hand speeds because longer distances must be covered in the same time. Playing the double bass consequently requires a specialized playing technique. In the lower registers fingers 1 to 4 are placed on the finger board and the thumb is placed behind the neck. Playing in higher registers requires using "thumb position". The thumb is placed on the finger board and is used to stop the string like a normal finger. Finger 4 is typically not used (Figure 1).

A shortened string will vibrate at a higher frequency, depending on the remaining length of the string, i.e. the position of first finger or thumb will determine the new frequency. In a high register the remaining string length will be shorter than in a low register (Figure 2).
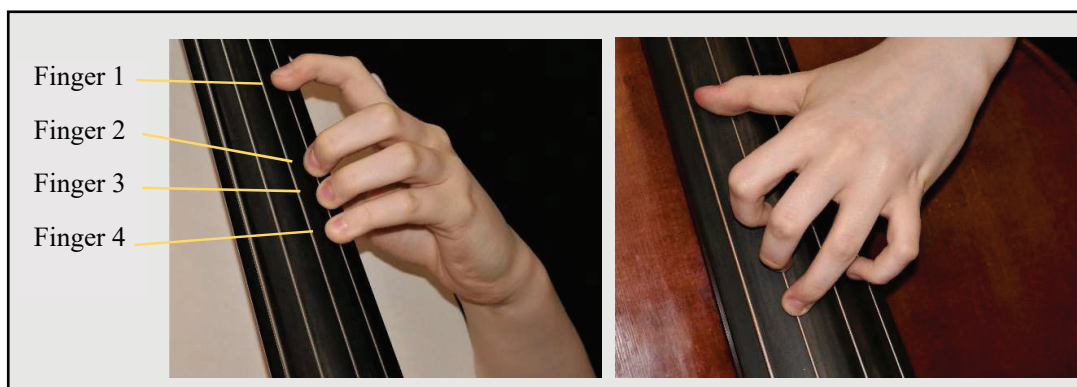
Figure 1: Finger positions on the fingerboard in a low and a high register
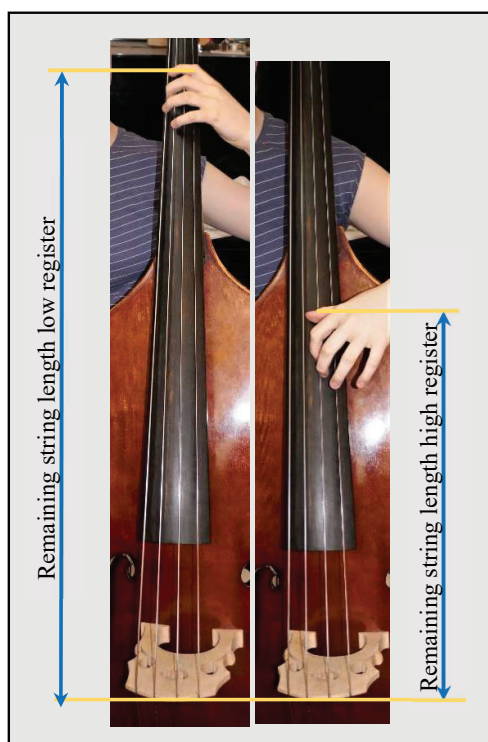

Figure 2: Remaining string lengths low and high register

From this basic position the other fingers of the hand will reach out to press down the string at a fixed distance. These distances correspond to musical intervals. Due to the variable remaining string length the same musical interval corresponds to a larger finger distance in a low register than in a high register. Using the same distance between the fingers will result in the musical interval becoming greater when moving up from a low register to a high register. Varying fret distances on electric basses represent this phenomenon.

minor 3rd	major 3rd	perfect 4th	perfect 5th	perfect 8th
minor 3rd	minor 3rd	minor 3rd	minor 3rd	mi.3rd
low register				high register

*Figure 3: constant distance - changing interval / constant interval – changing distance*

Keeping the fingers at a constant distance when moving along the finger board is a complex process. Our brain automatically coordinates the movements of all participating muscles, some contract and some stretch, based on our perception on where the finger at the end of the shoulder-elbow-arm-hand assembly should be. The complexity of coordinating all necessary movements will lead to a false perception of the finger distance. It is perceived to become smaller when moving the hand up the finger board. Naturally a bass player will counter this false perception by wrongly enlarging the space between the fingers thus compromising intonation.

Perfect perception and correct spacing between the fingers in any position on the fingerboard is therefore a very important parameter for a correct intonation. Using the advantages of additive manufacturing technologies a new approach to perceptional training shall be made by designing a mechanical training device to keep the fingers of the left hand at a fixed distance at all positions.

State of the Art

Different educational approaches have been made to kinesthetic and perceptional training on the double bass. Gannett has developed "Splints" [1] to create a perfect curvature of the fingers. However, no approach using a mechanical device for perceptional training of the correct finger spacing has been made until today.

An *orthosis* is "an externally applied device used to modify the structural and functional characteristics of the neuromuscular and skeletal system. … An orthosis may be used to: control, guide, limit and/or immobilize an extremity, joint or body segment for a particular reason…" [2]. Orthoses are mostly used for medical purposes to support the healing process of almost every part of the body after injuries or surgery by supporting or limiting the movements of joints.
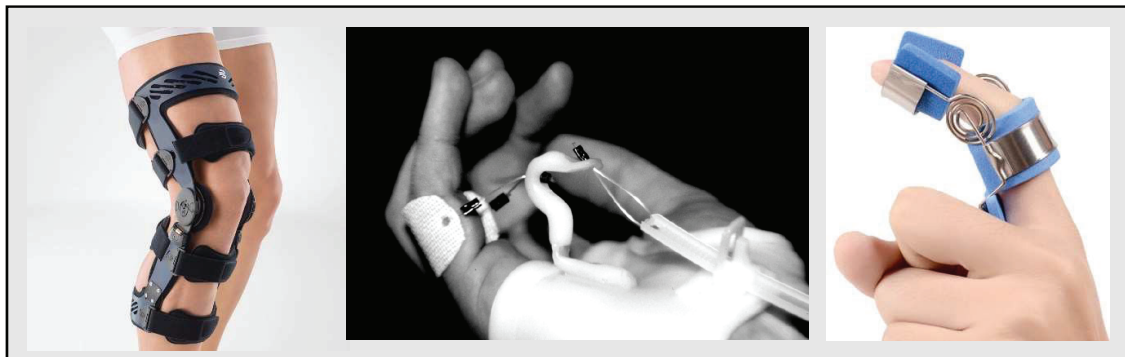
Figure 4: Knee orthosis supporting a knee with arthrosis [3], small finger mobilization orthosis [4], finger rehabilitation orthosis [5]

Orthoses protect soft tissue structures for healing purposes [4], making them comfortable to wear for longer periods of time. A variety of materials is used. Structural parts are predominantly made of carbon fiber, aluminum, steel-wire or thermoplastics. Parts in contact with the body are often plaster casted and then padded with fabrics, gel, air or foam cushions. Their dimensions complement the patient´s measurements and the required therapy determines their functions and mechanical structure. A finger orthosis for perceptional training in music pedagogy is new.

In the following chapters the Digital Product Development Process is used to allow a systematic and methodical design and manufacturing approach for design and additive manufacturing of the orthosis.

Digital Product Development Process

The ***Digital Product Development Process*** is part of the overall AM lifecycle [6].
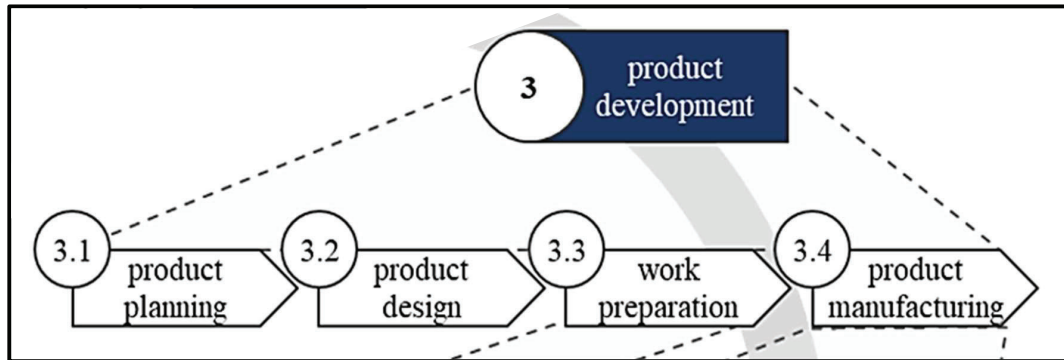

Figure 5: Product Development Process (detail) [6]

The methodical approach will focus on the ***Digital and Methodical Design Process*** (product design) in the context of a successive ***Additive Manufacturing Process*** (work preparation and product manufacturing).

The ***Digital Design Process***, based on the rules of Design Engineering Methodics [7] [8] [9] [10], has become standard for the design of new products. Amongst many others, e.g. Adam, Borstell and Arndt [11] [12] [13] have integrated the requirements of Additive Manufacturing technology into the existing design rules. Designing a new additively manufactured product requires a customized design process. Restrictions and potentials of the Additive Manufacturing Process have to be accounted for before and during the design process.
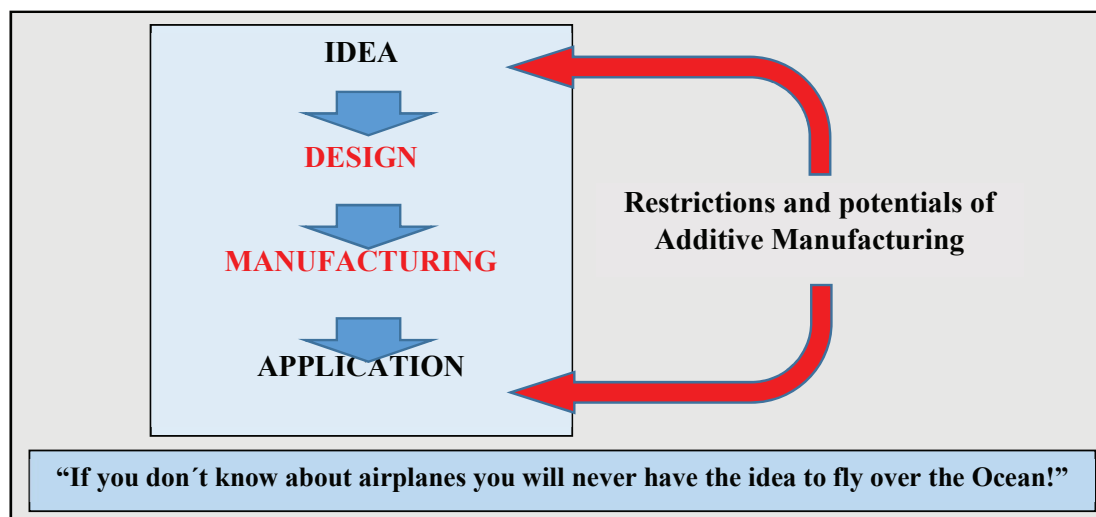

Figure 6: Product development process [12]

Simplicity is the key to the successful implementation of the designed device using AM in a completely non-technical environment. Each music student must be able to print his or her device scaled to the individual dimensions within one day (typically overnight) without AM expertise. Eliminating process steps demanding skills or knowledge in AM or design will

therefore be an important precondition. Digital Design Process, Pre-Process, In-Process and Post-Process [6] [13] contain different levels of required skills and have to be looked at. It is desirable to eliminate all process steps requiring special technical skills, i.e.:

- Scanning of the hand / fingers
- Creating and manipulating the digital CAD-model
- Saving the file as an STL-file (or similar)
- Setting the correct printing parameters (if not default settings can be used)
- Correct part orientation and positioning in the printer
- Generating optimum support structures
- Slicing of the STL-file (G-code)

Elimination of these design and pre-process steps from the overall process will eliminate sources of error due to non-skilled users. In-Process and Post-Process [13] are less demanding especially when using default printer settings. An unskilled user can print, clean and assemble the device selecting the right device-size from a set of pre-defined G-codes for different hand / finger sizes. This assumption must be validated.
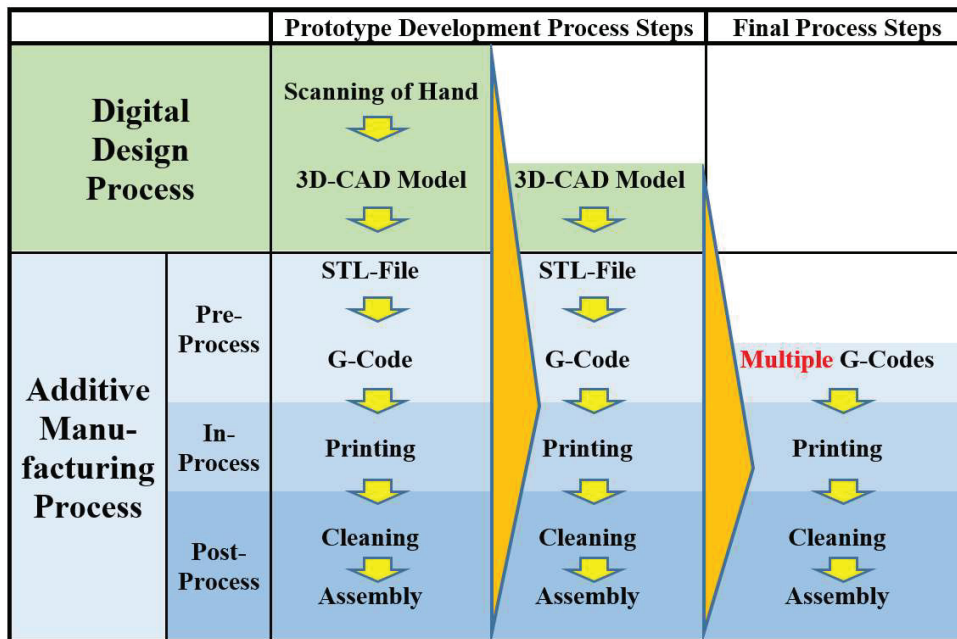
		Prototype Development Process Steps		Final Process Steps
Digital Design Process		Scanning of Hand ⬇ 3D-CAD Model ⬇	3D-CAD Model ⬇	
Additive Manu-facturing Process	Pre-Process	STL-File ⬇ G-Code ⬇	STL-File ⬇ G-Code ⬇	**Multiple** G-Codes ⬇
	In-Process	Printing ⬇	Printing ⬇	Printing ⬇
	Post-Process	Cleaning ⬇ Assembly	Cleaning ⬇ Assembly	Cleaning ⬇ Assembly

Figure 7: Simplification of the Product Development Process

Prototype development will go through all steps of the product development process applying the rules of the Digital Design Process.

Digital Design Process

Defining *requirements* and finding a *principal solution* are the first tasks of the Digital Design Process. The mechanical device will attach to the fingers during practice. Bass players have different finger- and hand-sizes. Finger-lengths and -diameters vary individually. Double basses have different sizes. The vibrating string length varies from 70 cm of a 1/16 children´s bass to over 107 cm for a 4/4 full size adult bass. The following requirements emerge:

- The device must be firmly attached to the left hand´s fingers without being uncomfortable wearing it for at least 1 hour
- The device must be individually adjustable to different hand and finger sizes (diameters and lengths)
- The spacing must be adjustable and lockable
- The device shall not hamper free movement of fingers and joints during practice
- The device shall not hamper acceleration of hand and fingers and must therefore be lightweight (less than 30 grams)
- Rapid manufacturing is necessary to make an individually sized device "on the spot", resulting in a total manufacturing time must be less than 6 hours (overnight)
- The manufacturing process must be simple enough for "non-skilled" personnel (musicians)
- Costs shall be less than $20 because the users will be students

(We must take into account, that some of the requirements cannot be measured using physical units and must therefore use perceptional feedback from end-users for evaluation.)

These properties make an orthosis a natural application for our purpose. Weight and cost requirements combined with low forces will allow using (cheap) thermoplastic materials. Manufacturing individually shaped three-dimensional surfaces in single numbers make AM the first choice for the manufacturing process.

Splitting up the design problem into abstract functions [7] [8] will result in simplified design tasks:
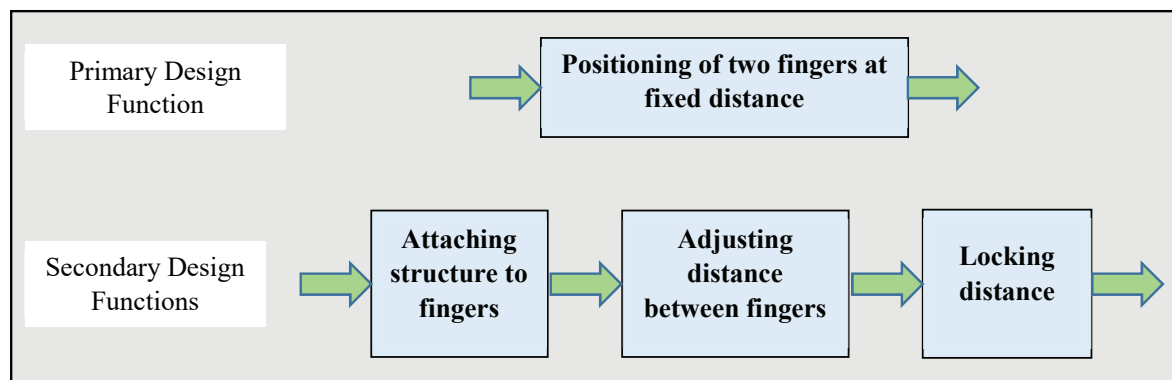

Figure 8: Design Functions

The ***primary design function*** is the positioning of two fingers (thumb and third finger) relative to each other at a fixed distance. It is detailed in the ***secondary design functions***, which are attaching of the structure to thumb and third finger, followed by adjusting the distance to the correct value and finally locking the device in that position.

Attaching structure to fingers

Attaching mechanical devices to human limbs is a task often solved in the process of designing an orthosis or prosthesis. Different approaches creating the contact surface to the human body are used. Making a ***plaster cast*** will result in embedding the cast itself in the device. No digital model exists. This method is therefore useless for AM. ***Scanning*** the surface of the limb will result in a digital model but require scanning hardware and data transformation into a 3D-CAD model [14]. Both require financial resources and skills. We cannot assume that these exist at a

School of Music. Complications arising when transforming scanned data into usable CAD-files furthermore make this approach impractical [15].

A simpler approach: measuring characteristic dimensions of the fingers with a sliding caliper and entering these values into an existing parametric 3D-model, thus eliminating the scanning step. When measuring dimensions at the characteristic positions the caliper must be closed tightly to the bone. An offset to these measurements will be created by comparing these dimensions to reference data and adding an offset representing the tissue.
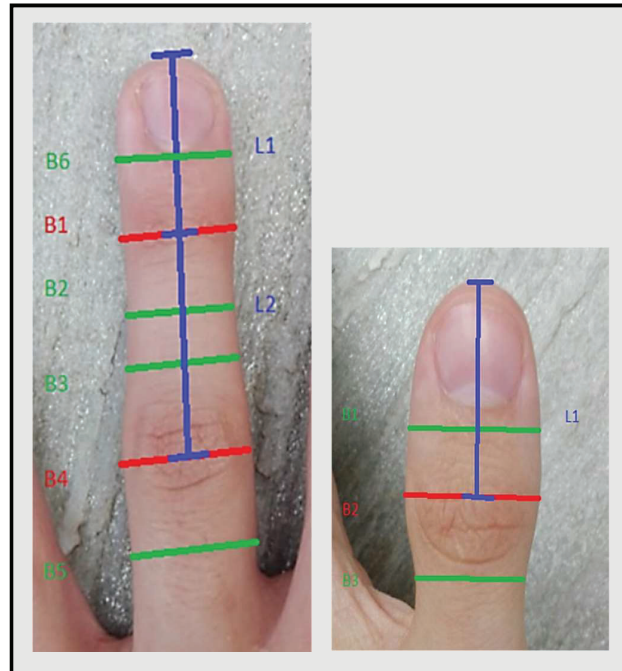

Figure 9: Characteristic dimensions of third finger and thumb [15]

For the prototype-model the dimensions of a representative bass player were taken, modified with the offsets and entered into the sketches and features of the CAD-model. Future validation of the prototype will result in a reduction of the number of characteristic dimensions and further reduce manufacturing complexity (see Figure 7).
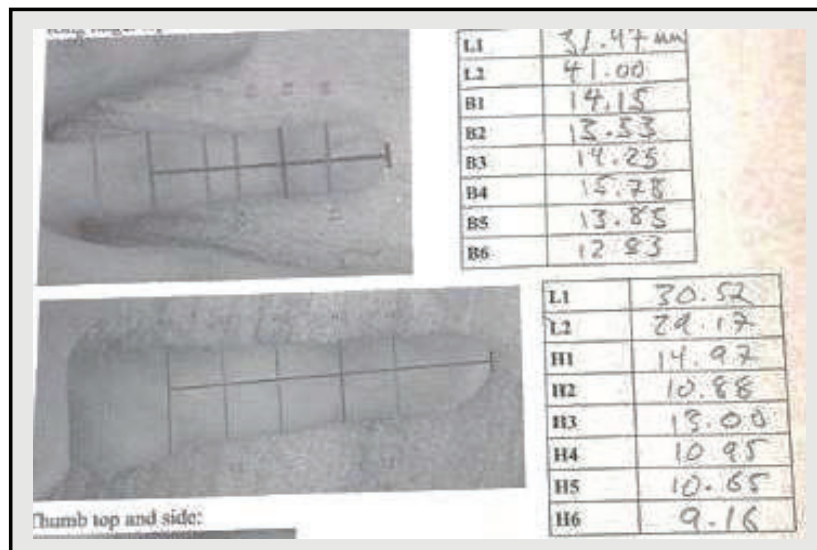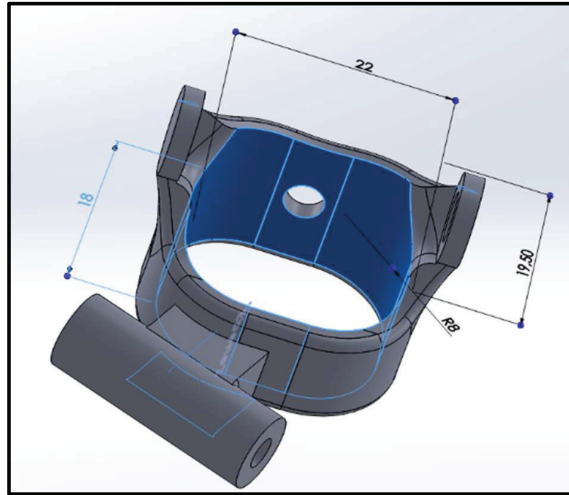

Figure 10: Third finger dimensions of representative bass player [15]

Figure 11: Characteristic dimensions in the 3D model of the lower section of the third finger [15]

The attachment to the finger consists of three thin shells connected by simple joints. Their dimensions are based on the measured data. The shell sections allow a comfortable and precise attachment of the device to the fingers. The model´s joint axles are aligned collinearly with the finger joint´s rotational axles allowing free movement of the fingers.
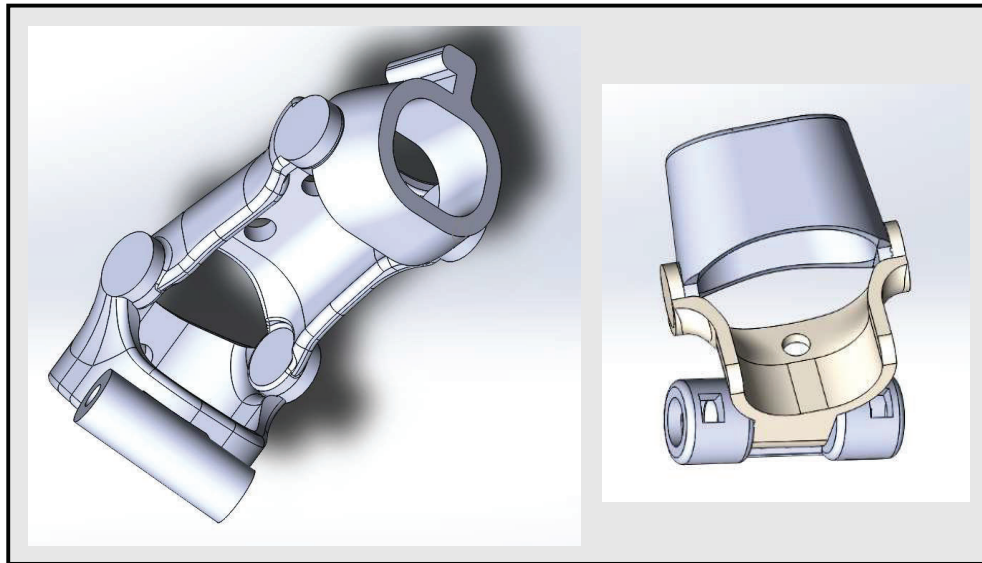
Figure 12: 3D model of the shells of the third finger and the thumb [15]

Adjusting and locking distance between fingers

Adjustment of the distance between the fingers is done by mounting the finger shells on two rods. The shell of the third finger is attached to the rods with a rotary joint using two screws. The shell of the thumb can slide along the rods. The distance is adjustable by sliding the thumb mount while the device is worn.

The locking mechanism consists of a friction wedge which will block the movement of the thumb shell if positioned against the lower part of the thumb shell.
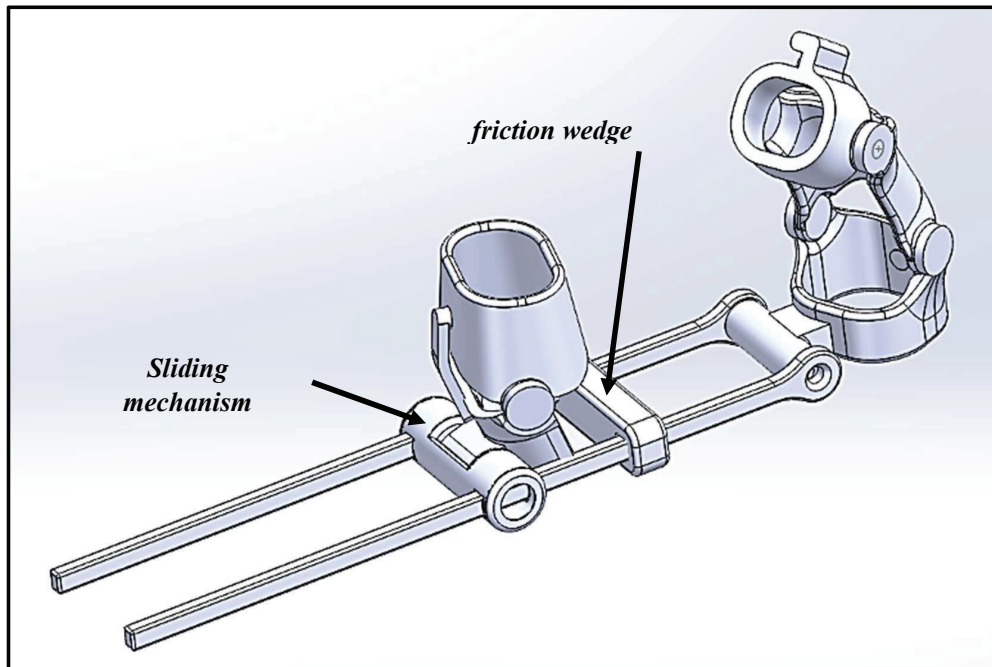

Figure 13: Adjusting and locking mechanism [15]

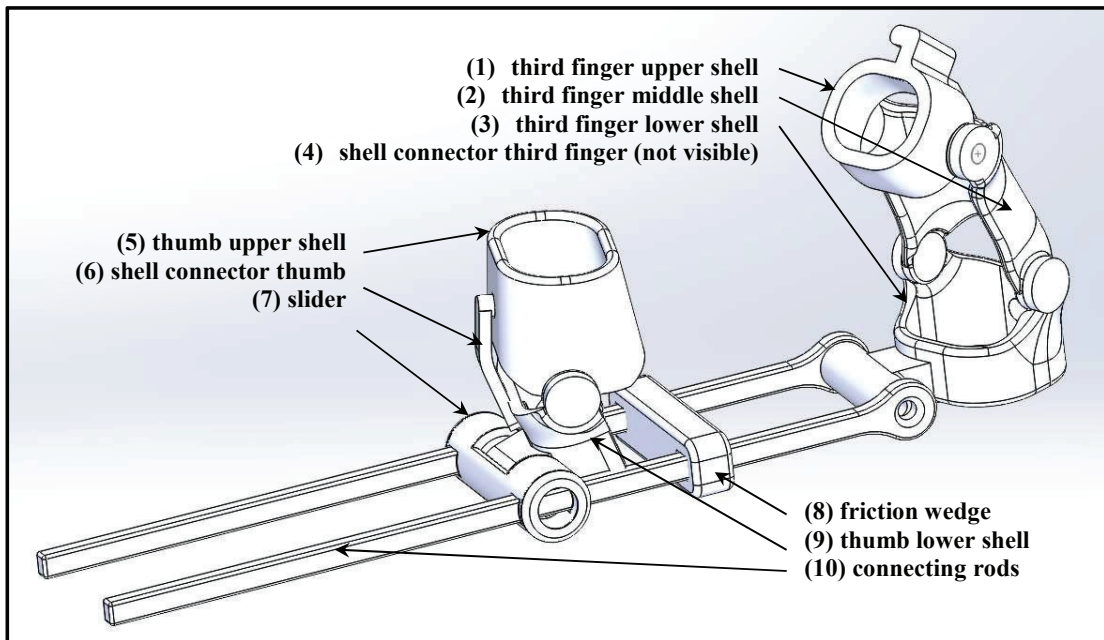The final result of the Digital Design Process is a complete digital model of the orthosis:

Figure 14: Digital model of orthosis assembly [15]

Additive Manufacturing Process

Simplicity of the manufacturing process postulates using as many default settings as possible. Selecting a default ***Printing Process*** compares FDM (Fused Deposition Modeling), SLS (Selective Laser Sintering) and STL (Stereo Lithography) processes [15]. These processes differ by the following criteria:

Properties	FDM **Fused Deposition Modeling**	SLS **Selective Laser Sintering**	SLT **Stereo Lithography**
Printing Speed	same as SLS, slower than SLT	same as FDM, slower than SLT	faster than FDM and SLS
Material selection independent of process	yes	yes	no
Handling characteristics	easy	skills necessary	advanced skills advised
Hardware price	low	high	medium
Operating costs	low	medium	medium
Support Structures	required	not required	required
Post Processing	remove support, smooth surfaces	sandblasting	wash in ethanol and harden with UV light

Table 1: Selection of default printing process [15]

Easy handling characteristics of an FDM printer in comparison to SLS and SLT printers is under the given conditions the decisive criterion for the default selection of the FDM printing process.

Availability and benign behavior preset the use of thermoplastic ***materials*** (excluding Nylon because of its high printing temperatures and abrasive behavior), leaving PLA, ABS and PETG. Table 2 highlights the selection on a relative basis:

	PLA	ABS	PETG
extruder temperature	200°C	260°C	240°C
bed temperature	20°C	70°-90°C	40°-70°C
glass transition temperature	50°-60°C	85°C	75°C
hardness	low	high	medium
elasticity	medium	low	high
finishing process	sandblasting, grinding	sandblasting, grinding, acetone vapor	sandblasting, grinding
mechanical properties in x-y-direction	medium	good	good
mechanical properties in z-direction	medium	bad	good
stringing tendency	low	low	high
warping tendency	low	high	medium

Table 2: Properties of available materials [15]

Superior mechanical properties (especially in z-direction), good temperature resistance and uncomplicated printing lead to the default selection of PETG.

As functionality is the primary design goal, additive manufacturing requirements are rated secondary. Standard slicer (e.g. CURA) functionality allows for simple optimization of the support structure and easy placement of the part in the printer to optimize printing time and layer orientation. As printing time is more important than tensile strength or surface quality, layer thickness and infill rate are set to intermediate values as defaults.
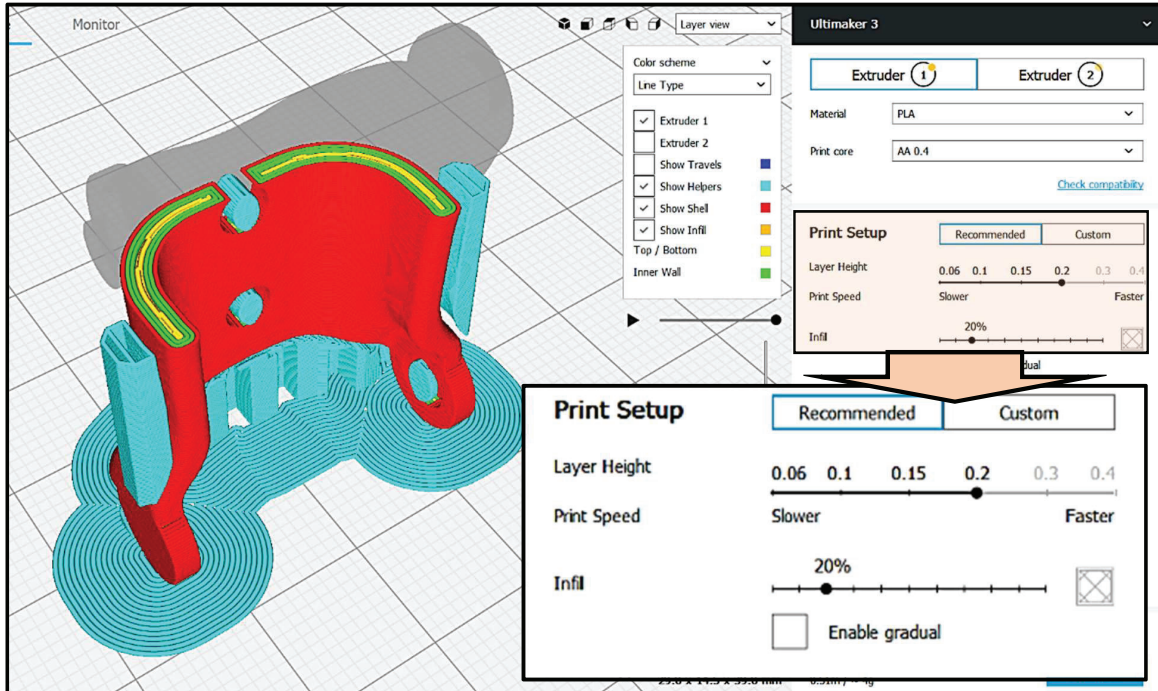

Figure 15: Default layer height (0.2 mm) and infill (20%) settings (CURA)

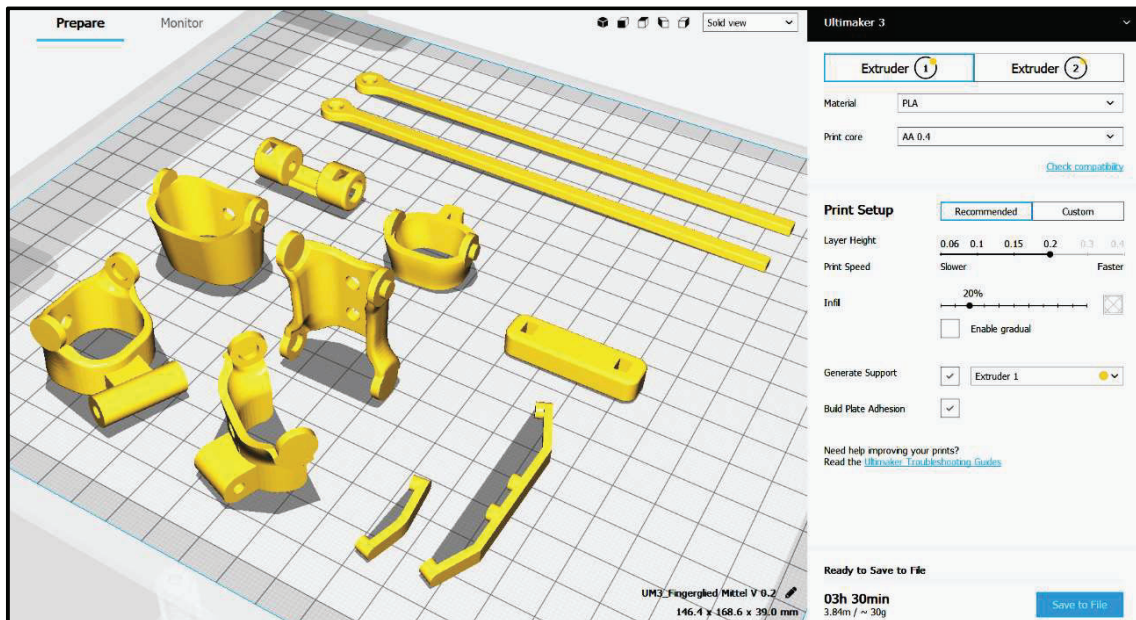All eleven parts easily fit into a standard FDM printer (e.g. Ultimaker 3).

Figure 16: Part´s arrangement in the printer using CURA

Calculated printing time will be 3 hrs. 30 min at a layer height of 0.2 mm and an infill rate of 20%. Weight will be around 30 grams.
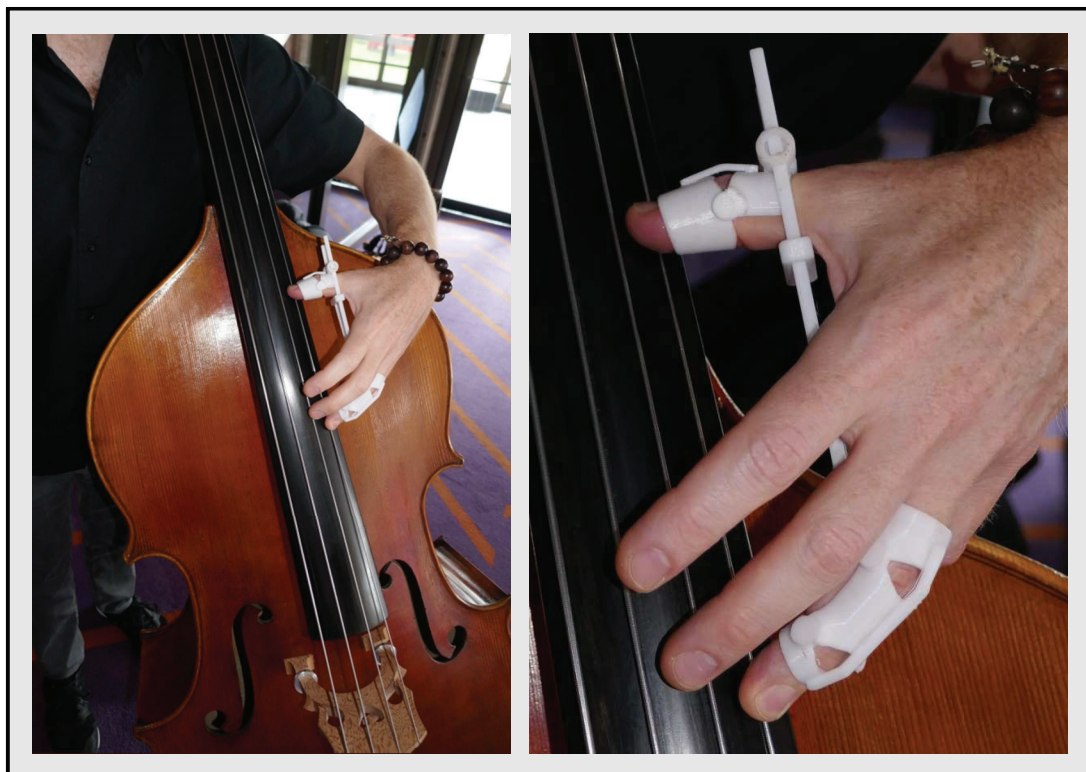
Prototype Validation

The device was printed according to the measured finger dimensions. All technical properties were according to specifications. Real weight of the printed orthosis including screws is 23 grams.

Figure 17: Prototype orthoses

Further validation was carried out by using it for perceptional training on the double bass.

Figure 18: Practical evaluation by representative bass player

It was fitting tightly without hampering movement of the fingers. When playing, a noticeable pressure against the outward facing sides of the fingers could be clearly felt, proving the theory of false perception of finger distances. Minor changes to the geometry of the thumb shell will be necessary to allow more parts of the thumb to be in contact with the finger board. The device will now enter further musical and educational evaluation.

Conclusion and Outlook

The application of additive manufacturing technology, design engineering methods and medical device technology to a problem from musical education was new and has led to a solution previously not possible. The methodical design of a 3D-printable orthosis was achieved by applying design engineering methods to the design process and to the AM manufacturing process. A prototype was manufactured on the basis of a default process using reference dimensions. The technical and educational evaluation of the prototype was successful. All technical and educational requirements have been met. The measured dimensions and offsets were accurate, the device was comfortable to wear and light enough to allow free movement of hand and fingers along the finger board. Minor geometrical modifications were suggested. A detailed educational evaluation with a larger number of test persons will follow in order to

- generate more data about standard finger and hand sizes
- define fixed orthosis-sizes e.g. XS, S, M, L, XL for easy printing of student´s devices
- define a standard simplified manufacturing process
- implement a test unit at a chosen location

With these steps implemented, the easy and low cost "on the spot" production of the training device will be possible at any location. The suggested simplification of the manufacturing process and the standardization of sizes highlight a method to exploit the huge prospects of AM technology not only in musical education but in a wide range of simple every-day applications.

References

[1] D. Gannett, "http://drgannett.com/practice-room/toys/splints/," 2019. [Online]. [Accessed 8 June 2019].

[2] Wikipedia, "https://en.wikipedia.org/wiki/Orthotics" 2019. [Online]. [Accessed 16 March 2019].

[3] Bauerfeind AG, "https://www.bauerfeind.de/de/produkte/bandagen/knie-huefte-oberschenkel/secutec-genu.html" [Online]. [Accessed 11 May 2019].

[4] D. F. E. Pitt, "Orthoses: Essential Concepts," in *Fundamentals of Hand Therapy*, C. Cooper, Ed., St.Louis, Elsevier / Mosby, 2014, 2nd Edition, pp. 103-114.

[5] OBER Shop, "www.amazon.de," [Online]. [Accessed 11 May 2019].

[6] C. Auth, D. Borstell and R. Anderl, "Knowledge-Based Material Production in the Additive Manufacturing Lifecycle of Fused Deposition Modeling," in *Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium*, Austin / Texas, 2018.

[7] R. Koller, Konstruktionslehre für den Maschinenbau, Berlin, Heidelberg: Springer Verlag, 1994.

[8] G. Pahl, Pahl / Beitz Konstruktionslehre, Methoden und Anwendung erfolgreicher Produktentwicklung, K. G. Jörg Feldhusen, Ed., Berlin, Heidelberg: Springer Verlag, 8 th Edition, 2013.

[9]   VDI, *VDI Richtlinie VDI 2225 Blatt 3, Design engineering methodics - enginering and design at optimum cost, Valuation of costs,* Düsseldorf: Verein Deutscher Ingenieure e.V., 1998.

[10] VDI, *VDI Richtlinie VDI 2225 Blatt 4, Design engineering methodics - enginering and design at optimum cost, Dimensioning,* Düsseldorf: Verein Deutscher Ingenieure e.V., 1997.

[11] G. Adam, *Systematische Erarbeitung von Konstruktionsregeln für die additiven Fertigungsvefahren Lasersintern, Laserschmelzen und Fused Deposition Modelling,* P. D. D. Zimmer, Ed., Paderborn / Aachen: Shaker Verlag, 2015.

[12] D. Borstell, *Lectures of the Research Laboratory for Additive Manufacturing, HS Koblenz,* Koblenz, 2018.

[13] A. Arndt, *Lectures of the Research Laboratory for Additive Manufacturing, HS Koblenz,* Koblenz, 2019.

[14] Z. Ma, J. Munguia, P. Hyde and M. Drinnan, "Development of a Customized CPAP Mask using Reverse Engineering and Additive Manufacturing," in *Final Program of the 29th Annual International Solid Freeform Fabrication Symposium 2018*, Austin / Texas, 2018.

[15] S. Kurz, "Konstruktion einer 3D-druckbaren Fingerschiene, Research Laboratory for Additive Manufacturing, HS Koblenz," Koblenz, 2018.

[16] VDI, *VDI Richtlinie VDI 2222 Blatt 1, Methodic deveoplopment od solution principles,* Düsseldorf: Verein deutscher Ingenieure e.V., 1997.

[17] Discover Double Bass Ltd., "https://discoverdoublebass.com/," [Online]. [Accessed 27 April 2019].

[18] International Organisation for Standardization ISO, *ISO 8549-1 1st edition,* Geneve: ISO, International Organisation for Standardization, 1989.

[19] A. Gebhardt, J. Kessler and L. Thurn, 3D-Drucken Grundlagen und Anwendungen des Additive Manufacturing (AM), München: Carls Hanser Verlag, 2016, 2.Auflage.

[20] A. Gebhardt, Generative Fertigungsverfahren, Additive Manufacturing und 3D Drucken für Prototyping - Tooling - Produktion, München: Carl Hanser Verlag, 2013, 4.Auflage.

[21] M. Schmid, Selektives Lasersintern (SLS) mit Kunststoffen, München: Carl Hanser Verlag, 2015.

[22] G. Abts, Kunststoff-Wissen für Einsteiger, 3rd edition ed., München: Carl Hanser Verlag, 2016.