REVIEW ARTICLE

Leveraging the Customizability and Rapid Production of 3D Printing in the Context of Prosthetics: A Review

Krish Jashnani

The Quarry Lane School, 6363 Tassajara Road, Dublin, California, 94568, USA; krishjashnani1@gmail.com

ABSTRACT: What if prosthetics could retain their customizability with more efficient production times and added material benefits? 3D printing is a method of seamlessly converting 3D modeled parts into real-life, rigid structures with varying infill patterns and densities, which can be used in the fabrication of limb prosthetics. With an estimated twofold increase in the number of U.S. residents using a prosthetic from 2005 to 2050, and 1.7 million patients using a prosthetic limb in the U.S. alone, the use of 3D printing can offer a customizable, affordable, and rapidly produced alternative or temporary replacement to traditional prosthetics. This paper aims to address whether the integration of 3D printing in the context of prosthetics promises meaningful benefits in terms of fit, ease of use, and production.

KEYWORDS: Mechanical Engineering, Biomechanics, 3D Printing, Compliance, Prosthetic Abandonment.

Introduction

The use of 3D printing to test-fit and develop custom prosthetics has changed the prosthetic industry.[1] Where bespoke parts took weeks to manufacture because they had to be machined with subtractive manufacturing, cast, or formed somehow else, 3D printing allows for the turnaround time to be in the 2-3 day range, while prebuilt and commercial-off-the-shelf (COTS) parts are used for the main workings:[2] COTS parts typically involve motion and power transfer, and cannot viably be 3D printed. Because 3D printed prosthetics are inexpensive, they are useful for applications where dimension and tolerance changes are commonplace, for example, a growing child. In this paper, factors such as mechanical properties, production costs, and evaluations of user experience will be used to evaluate the role of 3D printing in the context of prosthetics.

The main idea of 3D printing is that the outer topology of any digitally modeled solid form can be divided into vertically-stacked, two-dimensional cross-sections called "slices" through a computerized process known as "slicing".[3] The properties of this model are influenced by many factors, the biggest variable being the patient's human factors, taken through MRIs, CT scans, or other image processing.[4] The movements of motors and other actions required to lay material in these cross-sections are converted into g-code: coded instructions interpreted by the 3D printer and sent to its individual components to generate the processes necessary for the making of the 3D printed part. In this g-code are embedded instructions on how to create support structures as well, allowing for the making of sharp overhangs: structures that extend beyond the bounds of the previous layer. Within the slicing software, other parameters are set, such as infill pattern and density (affecting mechanical properties), nozzle temperature for fused deposition modeling printers, and exposure time for UV curing printers. After being processed from a 3D solid into a program readable by a 3D printer, the layers are solidified atop one another. After each layer, the print surface moves farther from the location where the solidified material is imparted: nozzle for a Fused Deposition Modelling (FDM) printer, or ultraviolet lamp in a UV curing printer.

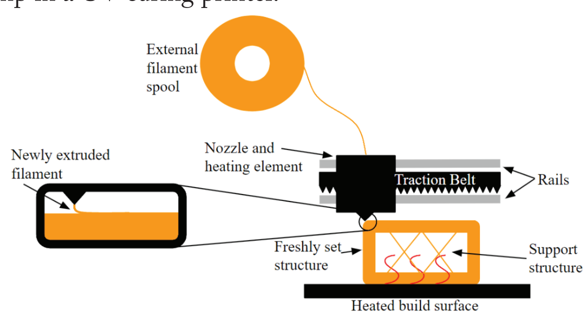

Figure 1: A simplified diagram of an FDM printerprinter's workings.

An FDM printer, pictured in Figure 1, operates akin to the icing of a cake. Both FDM printing and icing a cake both extrude the material from nozzles and must be stacked in layers to achieve the desired structure. This "icing," which is typically some kind of plastic, is shown here in orange, originating from a spool of wound-up, solid material. In the example of FDM printing, the uniced cake would be the heated print bed. Passing through a heating element on its way to the extrusion nozzle, which is constrained by rails and positioned by traction belts, it is extruded in layers so that the print head does not bump into structures above its current elevation while moving laterally. 3D printers read these solid forms as two-dimensional cross-sections and print layer-by-layer.[5] Note the support structure beneath the elevated surface; as filament cannot be laid in mid-air, support structures are required to sustain the printing of such layers. With proper speed, heating, and extrusion settings, support structures are not always necessary for mild overhangs.

DOI: 10.36838/v7i6.98

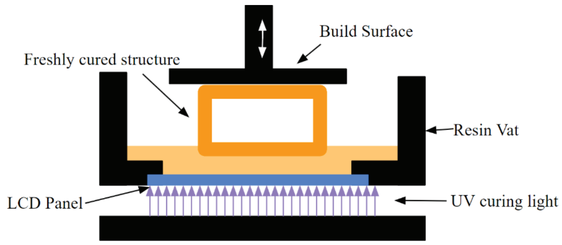

Figure 2: A simplified diagram of a UV curing printerprinter's workings.

Light curing, the other widespread form of desktop part synthesis, is simplified and shown above. Relying on a vat of liquid resin to supply its stock instead of a spool, resin is selectively cured by UV beams, the whole layer at once, or pixel by pixel.[5] Models print with their base facing upwards so that they have the maximum surface area contact with the base, meaning bonding between already cured resin with freshly cured resin makes printing overhangs far less forgiving. As a benefit of its solidification system, the resolution of prints is limited by only the UV beam width, making resin printing extremely precise. Furthermore, the lack of a laterally moving print head reduces wobble and contributes to print precision.

As is made evident by the diagrams, 3D printing is set apart from other manufacturing methods by its core functionality. It is an Additive Manufacturing method, meaning the material is added to the part until it takes the desired form.

To evaluate 3D printing's best-fit role in prosthetic manufacturing, its conformity to the standards that make prosthetics objectively good must be evaluated. It is quite well known that the two most pivotal factors to affect the usability of a prosthetic are comfort and mobility.[5-7] A lack of comfort causes a high rate of prosthetic abandonment, causing a waste of time, money, and material. Furthermore, users who previously experienced prosthetic abandonment may not return to prosthetics, resulting in greatly lowered limb functionality, skewed balance, and other drawbacks.[6] Bespoke prosthetics make up the majority of prosthetics, with 82.7% of prosthetics being cosmetically customized, and custom-fit prosthetics, both factors that disallow the effective continued use of previously abandoned prosthetics: as a result, it is best if prosthetic abandonment is kept to a minimum to reduce waste.[8]

Discussion

Democratizing Patient-Part Physical Fit:

Due to the complicated and varying nature of amputations, each stump's geometry differs. As a result, no matter whether limb prosthetics are mass-produced or bespoke, an adapter in between the stump and the limb is needed, known as a socket.[7,9] As sockets are a result of complex, unique stump geometry, and are present in any prosthetics involving residual limbs, sockets affect the fit of any prosthetic involving a residual limb.[7,9] Due to this, sockets are chosen as a subject to evaluate the effects of 3D printing in making custom-fit prosthetics widely available.

The process of attaining the stump profile for the traditional method of manufacturing involves making a plaster negative and using this mold to extract the profile. In this process, the mold must be destroyed as a result of having to break loose the now-solidified form inside. No records of the 3D geometry can be easily kept, meaning that for any changes in dimension or tolerance, the patient must revisit the clinic and endure the 2-5 week waiting period for traditional stump socket fabrication. Such constraints can cause issues in fit for growing children, and similar consequences apply to errors in mold formation, causing extra labor and time.[7]

The use of digital data to create a model of the stump is an alternative to attaining the stump profile through plaster molding. Patients wearing reflective dots or scanning socks have their stumps scanned, through a process like the one used to generate Computer Generated Images for movies. Scanning can take place optically or through the use of Light Detection and Ranging (LiDAR). In an attempt to recreate the stump manufacturing process with digital scanning and 3D printing instead of traditional methods, Olsen *et al*. used a low-budget optical scanning setup.[7] Erroneous or needlessly complicated artifacts in scans are then removed or flattened through the use of computer-aided design. The simplification of these artifacts makes for a better, more natural fit as detailed later. These scans can be saved digitally, eliminating the tediously repeated visits to the clinic each time measurements need to be made using the traditional method.[7] The storage of these 3D models also allows geometry to be shared, enabling worldwide review or transfer of the models. Then, using Cura (a slicing software) and Ultimaker printers, the sockets were sliced into machine-readable code and 3D printed. For Olsen *et al*., scanning and modifying took 32-45 minutes to attain a printable model. Autonomous printing took from 12 to 17 hours, and manual processing about 5 minutes: a major step up from the 2-5 weeks of traditional manufacturing. Given the wide range of FDM-ready materials, sockets cost 3 euros when being made with Polylactic Acid (PLA), which is a common 3D printing material. An antimicrobial copper-infused filament and medical grade PLA cost 9 and 10 euros respectively to print the same sockets, which only needed to be printed once, as opposed to a series of verification models required for traditional manufacturing.[10]

In the study done by Olsen *et al*., a participant stated that "...some of my sockets have required so many refitting sessions and visits to the clinic...it took so much time...you have demonstrated that you can create a socket that fits perfectly and has all the requirements including load bearing and has very little or no pressure points."[7] When achieving such custom fit is made far cheaper, quicker, and repeatable through the use of 3D printing, custom fit prosthetics will become far likelier to be selected as opposed to mass-produced, commercial off-the-shelf (COTS) prosthetics, which offer no input from the patient in terms of providing a comfortable, custom fit. As a result, the use of 3D printing can serve to democratize access to custom prosthetics by making them cheaper, quicker, less labor intensive, and repeatable, making them immune to the drawbacks typically associated with traditionally manufactured custom and COTS prosthetics.

Preserving Human Intuition in Prosthetic Mobility:

The retention of mobility being given the importance of 97.6/100 by Legro *et al.* in relation to prosthetics designates mobility as a core, high-priority factor in what makes such prosthetics sufficient for continued use to lower abandonment rates.[11] Because hands greatly affect the ability to carry out Activities of Daily Living (ADLs) through the use of mobility, the case of prosthetic hands will be studied to assess the effects of 3D printing's ability to contribute to the manufacturing of intuitive yet mobile hand prosthetics.[12]

Current traditionally manufactured prosthetics, in this case, ones that leverage myoelectric control, have an overly mechanically rigid construction. Due to the rigid structure, squeezing or gripping can impart a higher amount of pressure to the object than intended, even though the force remains the same. This lack of structural compliance and flexibility means more core modification must be done to render such a hand safe for human-object and human-human interaction. Examples of such efforts in modification are springs that add compliance, or tactile sensors necessitating the addition of another control loop.[13] These additional modifications add weight and increase the overall level of complexity of the operation of the hand, thus making it a worse candidate for everyday use: user acceptability rates drop, resulting in an abandonment rate of 40-60% for such hands.[14]

In the case of the XLimb, developed by Mohammadi *et al.*, the key focus for development was to make fabrication convenient while also allowing patients to regain the ability to carry out ADLs.[12] By leveraging the use of compliant structures in the making of the XLimb, several benefits arise, including making mechanisms cheaper and safer, and allowing the structure to be fabricated as one piece, where 3D printing shines. Previous utilizations of such a monolithic structure involve pneumatics, such as in the example of RBO Hand 2,[15] which normally saves weight through the lack of fasteners and other hardware. However, pneumatically actuated grasping must involve the use of valves and solenoids, and off-board gas storage, making the whole system oversized and heavy, thus greatly decreasing the prosthetic's general ease of use. In the case of the XLimb, which outlined mobility as one of its focuses, mechanical simplicity and ease of manufacture also worked to make 3D printing a perfect candidate for the fabrication of the hand.[12]

With the flexure joints of the one finger of the 3D printed XLimb detailed below, it is easy to see the XLimb's use of biomimicry due to the use of a monolithic structure: much like human tendons, the finger curls when a string running from the palm to the tip contracts. Because the weight of the actuators is centralized within the palm, and the minimized cantilevered weight in the fingertips (no fasteners are needed due to the 3D printed joints), the inertia of the XLimb is minimized, meaning less force is required to move it. As a result, XLimb becomes far more dexterous and intuitive to use as compared to other, traditionally manufactured prosthetics, exemplifying just another way where the use of 3D printing works to reduce the chance of prosthetic abandonment.

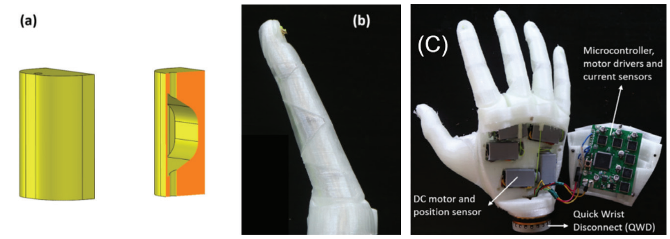

Figure 3: Finger detail (a,b) and individual working model (c) of the flexure joints and "tendonstendons" used in the XLimb, along with the openedopened-up palm, showing the actuators and microprocessor positioned as close to the wrist as possible.[12]

Category	Name	Weight (gr)	# DoF	# Actuators	Grip force (N) [Pinch, Power]	Grasp speed
Commercial						
	i-limb Ultra Revolution (Touch Bionics)	504	6	5	[6.54,136]	1.2 sec
	Bebionic (RSL Steeper)	495	6	5	[12.47,77]	1.9 sec
	Michelangelo (OttoBock)	420	2	2	[-,80]	-
	SensorHand (OttoBock)	350	1	1	[-,100]	300mm/s at tip
Research						
	Smart Hand	520	16	4	[-,18]	1.4 sec
	SoftHand Pro	520	2	2	[20,40]	1.5 sec
	Fluid Hand III	400	8	1 pump	[-,45]	1 sec
	Remedi	400	6	6	[-,9.2]	-
	X-Limb	253	13	5	[10.2,21.5]	1.3 sec
	MANUS Hand	1200	3	2	[-,60]	2.5 sec

Figure 4: Some of XLimbXLimb's statistics compared to other prosthetic hands, researchresearch, and commercial. Sorted by mass (descending). From https://doi.org/10.1371/journal.pone.0232766.t003 t003.[12, 20]

As shown above, the X-Limb is the lightest on the list, and 28.5% percent lighter than the second-lightest hand. Furthermore, it is one of the only hands with the available pinch function, a characteristic of adaptive and compliant prosthetics like X-Limb. These hands exert such contact force spread out over the area that conforms to the subject, rather than non-adaptive hands exerting concentrated force over a smaller area as they do not conform.[12,21] Lastly, because of the tendon-like actuation, the 3D Printed X-Limb is one of the quickest-grasping on the list, using the middle finger (the slowest). The tradeoff between fast grasping and forceful grasping can be adjusted by changing the dimensions of the spools holding the string "tendons".[12]

As a result of the 3D Printed, monolithic construction, the X-Limb can leverage lifelike, tendon-based actuation systems, decreasing the delay between the human's intent to grasp and when the actual grasping takes place. Also a benefit of the 3D Printed structure, X-Limb can centralize and minimize weight closer to the wrist, making operation and movement subject to less inertia. The 3DP-compliant body allows it to safely use the pinch function, unlike some other non-compliant hands. As a result, the operation of the X-Limb is made extremely intuitive and simple through the use of 3D printing, which makes it lighter, faster, and more lifelike than traditionally manufactured prosthetics.

DOI: 10.36838/v7i6.98

Production, Automation, and Scaling:

The RepRap, or Replicating Rapid Prototyper, laid the groundwork for what would become known as the "3D Printer".[3] The open-source project detailed and executed the requirements for a manufacturing machine that made as many of its own parts as possible, offering unparalleled customizability and scaling. Josef Prusa, founder of Prusa Research, embraced this idea as he started his own 3D Printing company, and when scaling Prusa Research's print farm to 600 printers running 24/7/365.[16] With it, in just 11 hours, a 3D Printer known as the MK4s can fabricate all the plastic parts for multiple other MK4s, with 98% percent of prints turning out perfect.[16] Much like changes in dimension for residual limbs or other changes in prosthetic modeling, Prusa can immediately begin production of new parts the moment they are improved, giving them a cut above injection molding where molds would have to be fabricated. In the case of 3D Printing, this traditionally fabricated mold would instead be the one made of plaster detailed in an earlier section of this paper. Furthermore, the print farm doubles as a rigorous testing environment, meaning that quality control issues resulting from extended use are ruled out before these versions are sold. In addition, conversion kits are sold each time new hardware updates are made, meaning organizations can upgrade older printers to more modern and reliable hardware upon release or budget availability. These factors make Prusa an efficiently scalable and upgradable candidate for print farms, which are a series of 3D Printers running simultaneously and controlled by centralized software to reduce turnarounds.

During the peak of the COVID-19 pandemic, Josef Prusa, in collaboration with the Czech Ministry of Health, developed and validated a rapidly manufacturable face shield for frontline medical workers. Recognizing print farms as a way to fill the need for equipment immediately, and free from the at-capacity-production model, Canadian tech YouTuber Linus Tech Tips stepped in to help ramp up production for his surrounding medical community. The one utilized by his company is manual: because the same parts are being made each time, the same print files are used as well, minimizing the need for centralized data management and job processing. All that needs to be done in between prints is to recognize that the print is complete, remove it from the print bed, reapply the protective layer (using a glue stick) on the print bed, and restart the process. Of course, occasional filament replenishments are required.[18] With this method, 300 face shields were produced a day.

In the case of prosthetics, however, the use of unique models each time necessitates the use of centralized, automated job management, as a result of on-demand manufacturing, like the one implemented by Radaviciute using Prusa printers.[17] OctoPrint, a minimally intensive 3D print management software allowing for the use of camera feeds to monitor prints, was chosen in the example detailed by Radaviciute, who implemented a 3D print farm in the Metropolia University of Applied Sciences. As it is open-source, many plugins for OctoPrint exist, allowing file and inventory management to be tailored to each use case.[22] As a result, Radavicute's print farm can be upgraded in terms of hardware and software as new iterations for both are released and can be managed centrally through the use of open-source software, making for a print farm that costs not much more than the printers themselves.

A step further is the Prusa AFS (Automated Farm System), a vending machine-like modular system that can be configured through the use of modules, allowing users to customize print storage and the number of printers. Centered around a 9 printer module (with the flexibility to add more such modules, up to 27 printers[19]), the AFS was made to reduce the need for human attendance to such farms. An example of another module is the shelving module, where the automated collection system places print beds with completed prints, and places empty, fresh beds on open printers. Data about what needs to be printed is processed into data about where it needs to be printed, and robotic systems for print collection and delivery, along with Prusa Connect software, allow maximized automation, allowing resources to be diverted to the maintenance of the printers themselves.[19]

If needed, a system like the AFS' automated print removal can be replicated for more accessible consumer use. A system made by Create it REAL, which can be adapted for use on many widely used, cost-effective 3D Printers,[22] is a form of simple-to-use automated print removal, meaning many prints can occur subsequently without human interaction. As shown in Figure 5, Create it REAL implements the mere addition of a fork to the print nozzle, and holes for the fork to the part (Create it REAL offers its own slicing software to streamline this process).[23] The fork, attached to the nozzle, approaches and catches these holes. Next, in Figure 5(b), the plate distances itself from the nozzle, peeling off the print in the process. Then, in Figure 5(d), the print is deposited. This also warrants modifications to the g-code so that the printer may make the extra movements necessary.[22] After the print bed is verified to be empty (either manually or with the use of computer vision), the next print can begin.

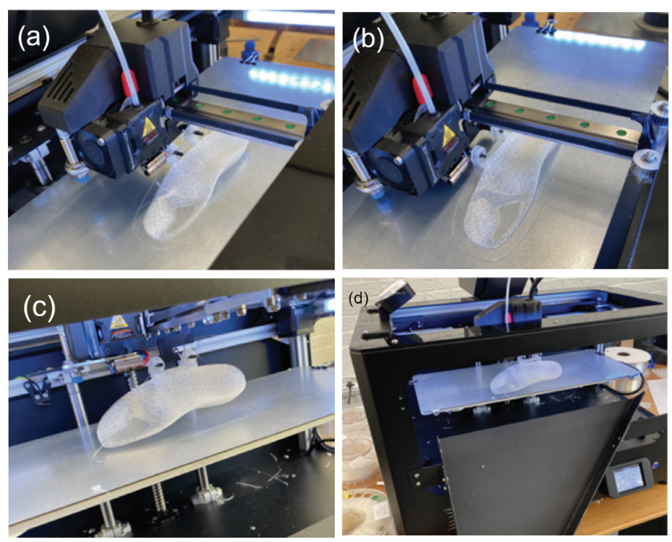

Figure 5: The operating steps of Create it REAL's automated print removal system.[22] 5a: The fork engages with the print. 5b: the print bed descends, separating the print bed and the printed part. 5c: the printed part is shown free from the print bed. 5d: The print head moves to the edge of the plate to deposit the print.

In conclusion, 3D printing need not be hindered in its use in prosthetics manufacturing: users can easily and simply set up "print farms," multiple printers interconnected by a centralized management software to minimize lead times and human interaction, thus maximizing efficiency while increasing the number of printers in an ecosystem. These print farms are customizable to the needs of any client.

Conclusion

This paper found that in terms of scaling production, preserving intuitive mobility, and making better fitting prosthetics are all aided by the incorporation of 3D Printing. The three factors are pivotal to ensuring that the ever-growing user base of prosthetics is less likely to abandon their use or stray from it in the first place.

As a result of modern digital technology, attempts to achieve a well-fitting prosthetic socket need not be limited by frequent, expensive, and inconvenient visits to the clinic. Instead, digital technology can be used to create a repeatable form of a patient's residual limbs, which can preserve or even outdo the performance of traditionally manufactured sockets.

Furthermore, the nature of 3D Printing allows it to create compliant, monolithic structures that far better emulate natural human mobility than traditionally manufactured, multipart hands by reducing the number of fasteners needed. This reduces inertia and centralizes weight, making the operation more intuitive. The compliant, 3DP monolithic structure also allows for fast grasping and use of the pinch function.

Lastly, the ease of use of 3D print farms makes scaling 3D printing production easily scalable by minimizing the human interaction needed and centralizing job management. Printers in these farms can be upgraded as needed, and farm management software is cost-effective and easy to adjust to customer needs.

Further research topics can involve finding the most optimal print farm configuration for medical and prosthetic use in varying scenarios, weighing factors like price, print accuracy, scope of printable materials, and speed. For this example, researchers may compare whether the upgradability of some printers, such as Prusa, is worth the extra initial cost, and whether customers with limited technical skill can upgrade them in the first place. Knowing now that 3D printing offers large benefits in production time and value, comfort, and use, manufacturers can design and plan the creation of prostheses accounting for such factors to further leverage 3D printing's influence on modern manufacturing.

Acknowledgments

I would like to thank Dr. Steve Bullock and Kieran Tait for their advice when writing this paper.

References

1. Venkatraman, V.; Poldrack, R.; Yeung, D. E.; Ulrich, M. D.; Ochsner, K. N. Regional variability in emotion regulation strategies: A critical analysis of the cognitive regulation of emotion. J. Cogn. Neurosci. 2008, 20 (4), 736–752. DOI: 10.1162/jocn.2008.20052.
2. Promedeast. Limb loss statistics. Accessed 2024-08-21. https://promedeast.com/limb-loss-statistics/.
3. Rengier, F.; Mehndiratta, A.; Von Tengg-Kobligk, H.; Zechmann, C. M.; Unterhinninghofen, R.; Kauczor, H.-U.; Giesel, F. L. 3D printing based on imaging data: Review of medical applications. Int. J. Comput. Assist. Radiol. Surg. 2010, 5 (4), 335–341. DOI: 10.1007/s11548-010-0476-x.
4. Jandyal, A.; Chaturvedi, I.; Wazir, I.; Raina, A.; Haq, M. I. U. 3D printing – A review of processes, materials and applications in Industry 4.0. Sustain. Oper. Comput. 2022, 3, 33–42. DOI: 10.1016/j.susoc.2021.09.004.
5. Poljak-Guberina, R. Patients' satisfaction with prosthetic devices. Coll. Antropol. 2005.
6. Olsen, J.; Day, S.; Dupan, S.; Nazarpour, K.; Dyson, M. 3D-printing and upper-limb prosthetic sockets: Promises and pitfalls. IEEE Trans. Neural Syst. Rehabil. Eng. 2021, 29, 527–535. DOI: 10.1109/TNSRE.2021.3057984.
7. Klute, G. K. Mechanical properties of prosthetic limbs: Adapting to the patient. 2001, 38 (3).
8. Lee, S.-P.; Mitchell, C.; Repayo, K.; Tillitt, M.; Weber, C.; Chien, L.-C.; Doerger, C. Patient engagement in cosmetic designing of prostheses: Current practice and potential outcome benefits. Prosthet. Orthot. Int. 2022. Accessed via U.S. National Library of Medicine. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9372180/.
9. Pasquina, C. P. F.; Carvalho, A. J.; Sheehan, T. P. Ethics in rehabilitation: Access to prosthetics and quality care following amputation. AMA J. Ethics 2015, 17 (6), 535–546.
10. Jin, Y.-a.; Plott, J.; Chen, R.; Wensman, J.; Shih, A. Additive manufacturing of custom orthoses and prostheses – A review. Procedia CIRP 2015, 36, 199–204. DOI: 10.1016/j.procir.2015.02.125.
11. Bártolo, P. J. High Value Manufacturing: Advanced Research in Virtual and Rapid Prototyping: Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal, 1-5 October 2013; CRC Press: 2013.
12. Legro, M. W.; Reiber, G.; del Aguila, M.; Ajax, M. J.; Boone, D. A.; Larsen, J. A. Issues of importance reported by persons with lower limb amputations and prostheses. J. Rehabil. Res. Dev. 1999, 36 (3), 155–163.
13. Mohammadi, A.; Lavranos, J.; Zhou, H.; Mutlu, R.; Alici, G.; Tan, Y.; Choong, P.; Oetomo, D. A practical 3D-printed soft robotic prosthetic hand with multi-articulating capabilities. PLoS ONE 2020, 15 (5), e0232766. DOI: 10.1371/journal.pone.0232766.
14. Jan, F.; Althoefer, K. Soft biomimetic prosthetic hand: Design, manufacturing and preliminary examination. In Proceedings of the International Conference on Intelligent Robots and Systems (IROS); 2018; pp 1–6. DOI: 10.1109/IROS.2018.8593666.
15. Biddiss, E. A.; Chau, T. T. Upper limb prosthesis use and abandonment: A survey of the last 25 years. Prosthet. Orthot. Int. 2007, 31 (3), 236–257. DOI: 10.1080/03093640600994581.
16. Deimel, R.; Brock, O. A novel type of compliant and underactuated robotic hand for dexterous grasping. Int. J. Robot. Res. 2016, 35 (1–3), 161–185. DOI: 10.1177/0278364915592961.
17. Jones, R.; Haufe, P.; Sells, E.; Iravani, P.; Olliver, V.; Palmer, C.; Bowyer, A. RepRap – the replicating rapid prototyper. Robotica 2011, 29 (1), 177–191. DOI: 10.1017/S026357471000069X.
18. PRUSA IN 2024. How we make our 3D printers. YouTube, 2024. https://www.youtube.com/watch?v=s8DybBlX55k.
19. Radaviciute, M. 3D printing farm set-up: Printers and software. n.d.
20. 3D Printing 300 Face Shields… PER DAY. YouTube, 2020. https://www.youtube.com/watch?v=HgPj6e3jtz0.
21. Inside Prusa's 3D Printer Factory. YouTube, 2023. https://www.youtube.com/watch?v=SCIOOlT3KJI.

DOI: 10.36838/v7i6.98

22. PRUSA PRO AFS - Automated Farm System: Presenting the Future of Manufacturing on EXPO 2020 in Dubai. YouTube, 2021. https://www.youtube.com/watch?v=uLMRAC2zJJA.
23. Prusa3D by Josef Prusa. Prusa Pro AFS | Original Prusa 3D Printers directly from Josef Prusa. Accessed 2024-08-21. https://www.prusa3d.com/applications/prusa-pro-afs_236928/.
24. Belter, J. T.; Segil, J. L.; Dollar, A. M.; Weir, R. F. Mechanical design and performance specifications of anthropomorphic prosthetic hands: A review. J. Rehabil. Res. Dev. 2013, 50 (5), 599. DOI: 10.1682/JRRD.2011.10.0188.
25. Kargov, A.; Pylatiuk, C.; Martin, J.; Schulz, S.; Döderlein, L. Comparison of the grip force distribution in natural hands and in prosthetic hands. Disabil. Rehabil. 2004, 26, 682–689. DOI: 10.1080/09638280410001704278.
26. Aagren, A. Printfarm management system. Master's Thesis, Aalborg University, 2023. https://vbn.aau.dk/ws/files/536077343/Master_Thesis_Alexander_Aagren.pdf.
27. Create it REAL. Tailored 3D printing solutions for orthopedics, prosthetics and others. Accessed 2024-08-21. https://www.createitreal.com/.
28. J., Lene. Is 24-7 mass-customisation really possible with FDM print? LinkedIn. Accessed 2024-08-21. https://www.linkedin.com/posts/jensenlene_technology-3dprinting-activity-7042058820197457920-GUr-/?utm_source=share&utm_medium=member_ios.

Authors

Krish Jashnani is a high school student at The Quarry Lane School in the 11th grade, interested in robotics and mechatronics. Following high school, Krish plans to study and research further in Mechanical Engineering in college.