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Investigation of Robotic System Parameters for 3D Scanning Human Limbs

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1. Introduction

Sockets for prosthetic limbs or orthopaedic aids are usually designed by measuring the relevant area through plaster wrapping, which is a tedious process involving wrapping multiple layers of plaster and waiting for it to harden. Such a process leaves a lot to be desired in terms of cleanliness, simplicity and speed, all of which can be improved by using 3D scanning instead. Current applications of 3D scanning for human body measurement mostly involve manual capture via handheld scanners, which often violates the optimal movement speed to resolution ratio, inflating scantime and error margins.

3D scanning of humans is a relevant field, which is highlighted by a multitude of influential research papers published in the past 5 years. Some research is review focused, summarizing existing scanning technology, use cases and issues in the field [1]. There are promising examples of uses for 3D scanning of people, such as measurement for custom hip brace manufacturing [2] or model acquisition for surgery simulation [3]. Some other noteworthy findings include facial scanning tests, where mean surface errors below 1 mm were recorded, confirming clinical viability of scanning for human anthropometry measurement [4, 5]. Hand specific scanning evaluations revealed the potential issues that can arise in such application and what deviation values to expect [3, 6, 7]. Regarding error, other studies tend to accept <1 mm average deviation but use experienced operators and long acquisition times [3, 8], which are more susceptible to problems related to inconsistency. Other useful studies are low-cost solution examples [9] and automatically generated prosthetic socket design [10].

The aim of this paper is to test for ideal motion speeds for a laser triangulation-based 3D scanner, which is mounted on a robot arm in order to ensure a certain speed is kept and to eliminate discrepancies in motion path. The mentioned robotic system is to be used on a manufactured replica of a human arm to quantify the velocity versus accuracy trade-offs that the different speeds provide.

2. Methodology

As this was not explored in recent similar studies, it is deemed significant to test the effects of scanner movement speed on scanning accuracy. The most reliable way to achieve that is to utilise a robot for scanner motion control, which allows for more precise testing than human motion can ever be. There are two main pieces of hardware that are used in the semi-automated robotic system, the first is ABB IRB 1200 robot arm, manufactured by ABB Robotics, based in Switzerland and Sweden, capable of carrying a payload of 7 kg in 6 separate axes of motion and repeatability of +- 0.01 mm. The second is the scanner HandyScan 700 (2015 ed.), manufactured by Creaform, based in Canada, it works with the laser triangulation principle and is able to capture 480,000 measurements per second, at a resolution of up to 0.2 mm. The scanner is attached to the robot toolhead via a custom designed adapter that is rapidly manufactured using fused filament fabrication with polylactic acid (PLA). This is sufficient to hold the scanner securely since it only weighs approximately 0.85 kg. The final experimental setup that was used is displayed in Fig. 1.

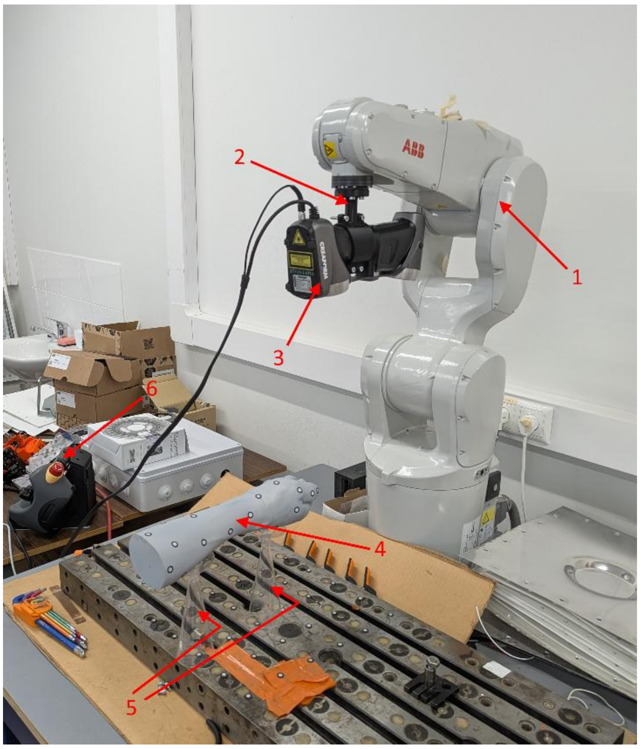

Fig. 1 Experimental setup of robotic system, here: *1* – ABB IRB 1200; *2* – adapter; *3* – HandyScan 700; *4* – 3D printed arm; *5* – see-through supports; *6* – control panel

In order to test the system parameters, a static human arm replica had to be manufactured, since a real hand would involve inherent movement due to biological factors, as well as possible angle changes of the wrist or elbow, leading to difficulties in comparing scans. This hand replica, which was also manufactured using 3D printing, is placed around the centre of the robot arm table, on top of two transparent supports, which are mostly invisible to a laser scanner. For better scanner performance and orientation purposes, the static hand is covered with a grey-matte primer and 40 targets are placed all around it, with a focus on more sudden curvature change areas. To attain a better 3D perspective, targets are also placed on the surface below the subject, 30 in total were placed approximately 10 cm apart.

Regarding motion path, best results overall were displayed by three half-circle sweeps of 335 mm radius, with forward advancement of 120 mm between them. The robot path is visualised in simulation software "RobotStudio 2025", shown in Fig. 2. Full circles were impossible to achieve due to the required distance of minimum 300 mm to the subject and limited robot reach, which in turn required two scans to be conducted per test – one for the top and the other for the bottom of the hand replica. Since the scanner's software (VXelements 12) has full functionality for scan merging, it was possible to easily attain complete hand scans. This was further facilitated by the large amount of targets used, resulting in at least 3 matching points for top and bottom scans.

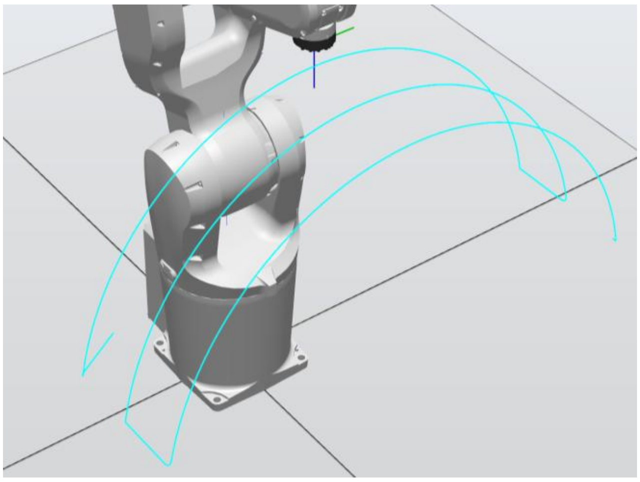

Fig. 2 Final robot path visualization in "RobotStudio 2025"

The main experiment conducted was testing of the relationship between scanner resolution, motion speed, standard deviation and captured surface area. After experimentally determining that the best laser exposure time for this application was 2 ms, several scan sequences were run at varying maximum motion speeds. The robot arm has preset speed configurations that only change the maximum toolhead speed, while other metrics, such as orientation speed (500 °/s), linear external axis speed (5000 mm/s) and rotating external axis speed (1000 °/s) remain static; each preset is prefaced with a "v" and then a number (e.g. "v100"). The fact that maximum orientation speed remains the same in all presets, combined with the nature of this programmed movement (almost purely circular) resulted in diminishing returns past 1000 mm/s maximum toolhead speed, as shown in Fig. 3. According to robot arm manufacturer specifications, this orientational speed cap cannot be further increased, so toolhead speed presets of v1500 and v3000 do not have significant practical applications in this use case. However, results still displayed worsening accuracy at speeds beyond 1000 mm/s and were therefore included in the tests and their results.

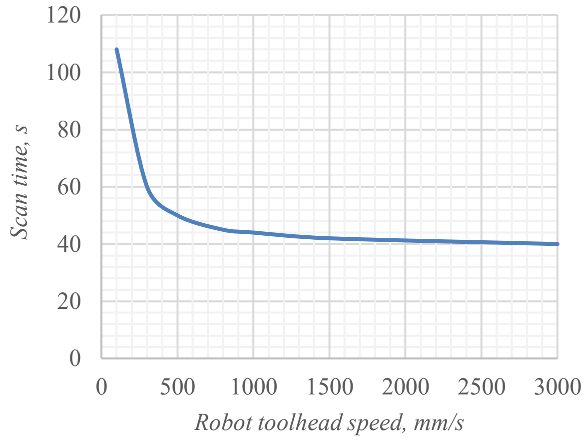

Fig. 3 Graph of toolhead movement speed and total scan time

Testing was carried out with 7 different movement speed presets (v100, v300, v500, v800, v1000, v1500, v3000), at 4 scanner point cloud resolutions (0.2, 0.6, 1.0, 2.0 mm), slowest time was 40 s, fastest – 108 s. Each configuration had 3 repetitions for both the top and bottom replica hand scans, with the average being used in comparisons and plotting. Scan results were evaluated also by using the scanner's software (VXelements 12), where a reference mesh is imported, which was the original hand mesh used for fabricating the replica, and then compared to merged scan results. Two main metrics were assessed: scan surface area, which shows how complete a scan was and how usable it could be; surface standard deviation, showing how far away points of the captured mesh are from the reference surface on average. Figures below highlight the results that are seen when evaluating scan accuracy, Fig. 4 shows a colormap that is generated on the mesh, Fig. 5 displays error distribution.

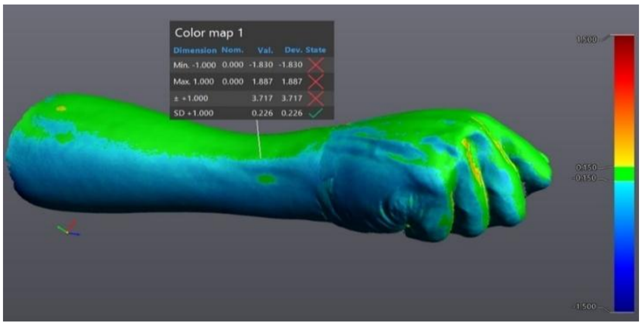

Fig. 4 Colormap view on the mesh in "VXelements 12"

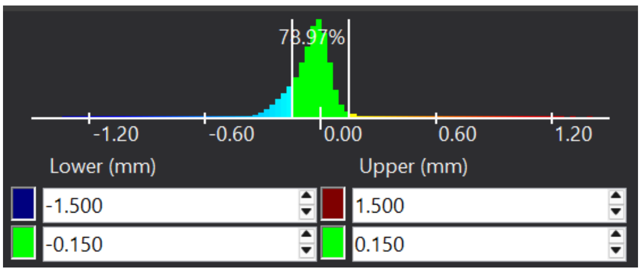

Fig. 5 Error distribution chart in "VXelements 12"

4. Results

As illustrated in the graph of speed vs covered surface area shown in Fig. 6, all of the tested resolutions achieved highest area coverage at 100 mm/s speeds, showing that overexposure benefits scan completeness. The standard deviation results, displayed in Fig. 7 indicate that decreasing scan resolution allows for faster movement speeds, even beating lower ones. This shows a clear trend, the higher the resolution, the more surface area can be captured per second in a sweep. For 0.2 mm resolution, deviation values peaked at 100 mm/s, while for 0.6, 1.0 and 2.0 those peaked at 300, 500 and 1000 mm/s respectively. The highest resolution of 0.2 mm was, as expected, the most accurate, but significantly more prone to scanning errors and unusable at higher speeds as surface area completely tanked. All tests stayed within clinically acceptable norms of ± 1 mm deviation, which is relevant for rigid sockets and some orthopaedic devices.

It is not entirely certain which configuration is best, although some suggestions can be inferred from the data. Recommended configurations for human limb scanning are resolution of 0.6 mm at 300-500 mm/s speeds, as these seemed to perform overall the best. For more rapid applications, lower resolutions would have to be used as the high ones start to lose surface area with increasing speeds. Other results, such as average error peaks presented in Table 1, suggest that higher speeds and lower resolutions also increase error margins, which once again favours the 0.6 mm resolution. In future studies, it would be beneficial to test a more recent scanner that can capture more points per second (1 million or above), which should allow for much higher speeds even at high resolutions.

As mentioned before, surface standard deviation is by far the most reliable metric at evaluating scan accuracy. There are other metrics that can provide insight however, such as maximum and minimum error values. Table 1 displays the average values retrieved in this study, where a similar trend to standard deviation can be seen, with higher resolutions resulting in lower errors. These results are not as uniform however, with some values seemingly not changing or fluctuating at random, which could be caused by vibration during robot motion, especially present at higher speeds. In some literature, clinically acceptable error margins are said to be± 1 mm, which in this case would be only accepted for 0.2 and 0.6 mm resolutions at the lowest speed setting. However, since this metric does not appear as dependable numerically, with values changing only slightly with differing settings and resolution does not affect it as significantly as standard deviation or surface area coverage did.

In general, tests were successful and showed that there is an ideal speed for each scanner resolution, which is also dependent on the maximum points per second that can be recorded. Regarding scan merging – some tests were done to assess whether it has any significant impact on results. After 7 scans under identical conditions, surface

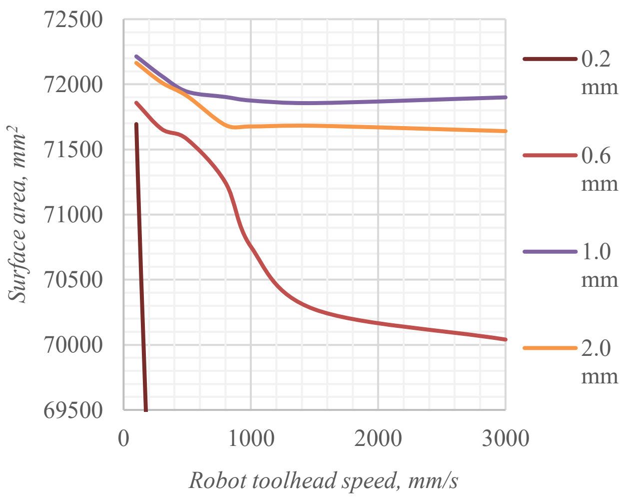

Fig. 6 Plot of toolhead movement speed vs surface area at 4 different resolutions (0.2, 0.6, 1.0 and 2.0 mm)

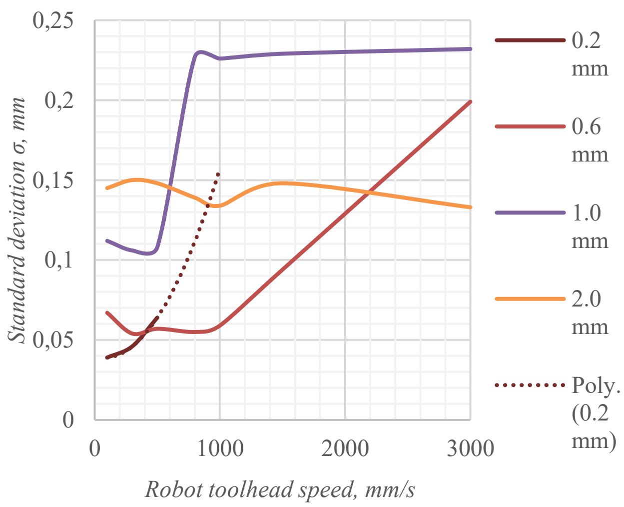

Fig. 7 Plot of toolhead movement speed vs standard deviation at 4 different resolutions (0.2, 0.6, 1.0 and 2.0 mm)

Table 1

Average values of minimum and maximum errors reported in tests

Speed Preset, mm/s	0.2 mm		0.6 mm		1.0 mm		2.0 mm	
	Min. error, mm	Max. error, mm	Min. error, mm	Max. error, mm	Min. error, mm	Max. error, mm	Min. error, mm	Max. error, mm
v100	-0.684	0.889	-0.653	0.938	-1.642	0.914	-1.660	1.804
v300	-0.667	1.645	-1.141	0.412	-1.417	0.755	-1.724	1.951
v500	-1.308	1.774	-1.337	0.739	-1.596	1.506	-1.816	1.949
v800	-	-	-1.159	1.689	-1.475	1.429	-1.909	1.956
v1000	-	-	-1.198	1.695	-1.675	1.707	-1.530	1.961
v1500	-	-	-1.205	1.656	-1.617	1.521	-1.933	1.860
v3000	-	-	-1.258	0.902	-1.482	1.528	-1.447	1.995

standard deviation varied by no more than 0.05 mm when comparing merged and non-merged scan accuracy. Similarly, scanner noise was evaluated to be 0.0277 mm on average, which was retrieved by comparing said scans to each other. Although scan merging is not an issue for static hand replica measurement, it would likely cause problems for real human scanning. In order to prevent this, it is recommended to switch to a robot arm with higher reach that can cover all of the hand's surface area, rather than the ~70 % possible in this system configuration. Furthermore, supports should be improved such that motion blur is avoided, which could significantly deteriorate result accuracy. It is also worth noting that for literal human scanning, safety measures must be put into place to ensure no accidents occur in the form of collisions.

5. Discussion

All in all, this study found that automation of the handheld scanner can improve scan accuracy by ensuring a consistent, ideal movement speed for the specific scanner and its parameter configuration. Results can easily be extrapolated to other robots and scanners, as the core principle remains unchanged regardless of what hardware is used. With some further research following up on this concept, it would be possible to mathematically derive an equation that calculates the ideal movement speed for a given scanning device, which limits points per second captured and the chosen resolution.

Practical implications of this work are also important, especially in clinical settings. Although some further development of the system is needed in the form of choosing a robot arm with longer reach and better human-safety, as well as improved supports that could better accommodate a real human limb, which would also in turn allow for both leg and hand scanning. After such advancements are made, automated human scanning has significant potential in orthopaedics and prosthetics, particularly when it comes to the measurement and prototyping part of manufacturing aids. Essentially, 3D scanning is not implemented widely enough in such settings mainly due to the sheer amount of know-how needed to troubleshoot issues and conduct scans often, not to mention the time costs. Automation of such a process would allow for rapid prototyping of socket joins for prosthetics and orthoses, which would reduce the number of visits needed to the clinic, helping patients. Looking further into the future, it would be possible to set up autonomous scanning kiosks that offer scanning services for patients locally, without needing to wait long for multiple visits to the specialised doctor.

Another closely related topic is rapid manufacturing, including methods such as fused filament fabrication. This can directly take scanning results retrieved and create a negative that could be manufactured as a prototype to test patient comfort and quality of the fit. A problem in this field is the manufacturing of complex planes, which are often difficult to print and end up inaccurate or outright fail to be completed. To solve that, it could be possible to implement incremental sheet-forming (ISF) via robot arm for example. ISF is a method of forming a sheet of material gradually without the use of a die into a desired 3D shape. Some of the advantages are high flexibility, low cost, easy to prototype, although the accuracy is limited. This technology was tested shortly with the same robot in this work, Fig. 8 depicts the system setup for such testing and in Fig. 9, an example result of a formed socket prototype for an elbow is shown.

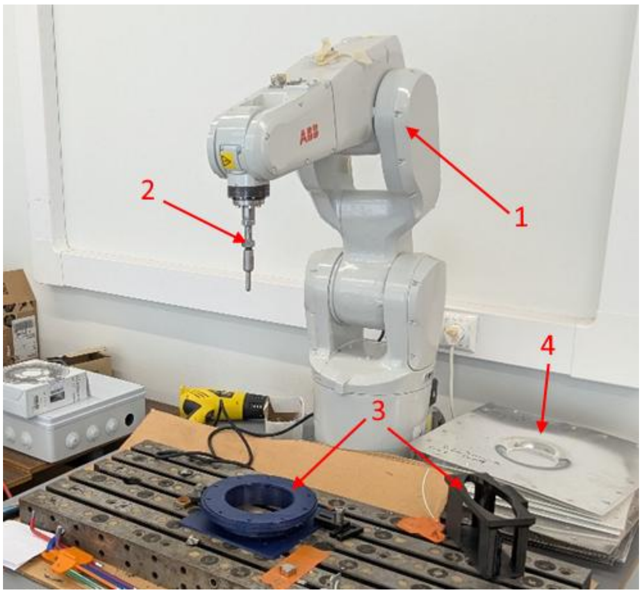

Fig. 8 System setup example of plastic sheet forming, here: *1* – ABB IRB 1200; *2* – toolhead with rounded end for smooth pressing; *3* – printed sheet holders to keep samples in place; *4* – formed metal sheets

Fig. 9 Example formed part, negative of a knee

6. Conclusions

1. The semi-automated scanning system, including the robot arm ABB IRB 1200 and the handheld scanner HandyScan 700 was implemented successfully. Due to limitations in robot reach, full scans were not possible and had to be done separately for both sides of the hand, which are then merged. No significant difference was recorded between merged and non-merged scans. A 3D printed replica of a person's hand was used instead of a real one in testing in order to ensure no motion blur or joint angle change occurred. The system was able to scan a limb in 40-108 seconds depending on the speed setting, with noise of 0.0277 mm on average.

2. Motion speed of the robot toolhead had a noticeable impact on surface standard deviation, showing benefits of automation beyond simply reducing random errors and speeding up the process. Specifically, for resolutions used (0.2, 0.6, 1.0, 2.0 mm), deviation reached a minimum at differing speeds (100, 300, 500, 1000 mm/s respectively). The lowest recorded standard deviation was 0.039 mm for the 0.2 mm resolution at 100 mm/s speed.

3. The system is not fully ready for real human scanning due to missing safety measures and inability to scan the entire surface in one go (only ~70%), as well as inadequate supports for motion blur reduction. All of these

issues can be solved by utilizing a different robot arm, which would have longer reach and more human-safe features.

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References

1. **Bartol, K.; Bojanić, D.; Petković, T.; Pribanić, T.** 2021. A Review of Body Measurement Using 3D Scanning. *IEEE Access*, 9: 67281-67301. https://doi.org/10.1109/ACCESS.2021.3076595.
2. **Kim, B. R.; Yoon, J. A.; Han, H. J.; Yoon, Y. I.; Lim, J.; Lee, S.; Cho, S.; Shin, Y. B.; Lee, H. J.; Suh, J. H.; Jang, J.; Beom, J.; Park, Y.; Choi, J.-H.; Ryu, J. S.** 2022. Efficacy of a Hip Brace for Hip Displacement in Children With Cerebral Palsy: A Randomized Clinical Trial, JAMA Network Open 5(11): e2240383. https://doi.org/10.1001/jamanetworkopen.2022.40383.
3. **Rudari, M.; Breuer, J.; Lauer, H.; Stepien, L.; Lopez, E.; Dragu, A.; Alawi, S. A.** 2024. Accuracy of Three-dimensional Scan Technology and Its Possible Function in the Field of Hand Surgery, Plastic and Reconstructive Surgery - Global Open 12(4): e5745. https://doi.org/10.1097/GOX.0000000000005745.
4. **Pellitteri, F.; Scisciola, F.; Cremonini, F.; Baciliero, M.; Lombardo, L.** 2023. Accuracy of 3D facial scans: a comparison of three different scanning system in an in vivo study, Progress in Orthodontics 24: 44. https://doi.org/10.1186/s40510-023-00496-x.
5. **Major, M.; Mészáros, B.; Würsching, T.; Polyák, M.; Kammerhofer, G.; Németh, Z.; Szabó, G.; Nagy, K.** 2024. Evaluation of a Structured Light Scanner for 3D Facial Imaging: A Comparative Study with Direct Anthropometry. Sensors 24(16): 5286. https://doi.org/10.3390/s24165286.
6. **Yu, F.; Zeng, L. Pan, D.; Sui, X.; Tang, J.** 2020. Evaluating the accuracy of hand models obtained from two 3D scanning techniques, Scientific Reports 10(1): 11875. https://doi.org/10.1038/s41598-020-68457-6.
7. **Schipper, J. A. M.; Merema, B. J.; Hollander, M. H. J.; Spijkervet, F. K. L.; Dijkstra, P. U.; Jansma, J.; Schepers, R. H.; Kraeima, J.** 2024. Reliability and validity of handheld structured light scanners and a static stereophotogrammetry system in facial three-dimensional surface imaging, Scientific Reports 14(1): 8172. https://doi.org/10.1038/s41598-024-57370-x.
8. **Powers, O. A.; Palmer, J. R.; Wilken, J. M.** 2022. Reliability and validity of 3D limb scanning for ankle-foot orthosis fitting, Prosthetics and Orthotics International 46(1): 84–90. https://doi.org/10.1097/PXR.0000000000000066.
9. **Farhan, M.; Wang, J. Z.; Warncke, R.; Cheng, T. L.; Burns, J.** 2024. Comparison of accuracy and speed between plaster casting, high-cost and low-cost 3D scanners to capture foot, ankle and lower leg morphology of children requiring ankle-foot orthoses, Journal of Foot and Ankle Research 17(3): e70006. https://doi.org/10.1002/jfa2.70006.
10. **Górski, F.; Wichniarek, R.; Kuczko, W.; Żukowska, M.** 2021. Study on Properties of Automatically Designed 3D-Printed Customized Prosthetic Sockets, Materials 14(18): 5240. https://doi.org/10.3390/ma14185240.

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INVESTIGATION OF ROBOTIC SYSTEM PARAMETERS FOR 3D SCANNING HUMAN LIMBS

S u m m a r y

This paper presents the investigation of motion speed effect on scan accuracy and in turn, automation benefits for a semi-automated 3D human limb scanning system. The robot arm ABB IRB 1200 was used in combination with HandyScan 700 handheld scanner to scan a human hand replica, achieving average noise of 0.0277 mm. It was found that for each resolution setting of a scanner, there is an ideal motion speed that maximizes accuracy. In this case, resolutions of 0.2, 0.6, 1.0 and 2.0 mm were tested at max toolhead speeds 100, 300, 500, 800, 1000, 1500 and 3000 mm/s, where minimal standard deviation values were found at 100, 300, 500, 1000 mm/s speeds for each resolution respectively. Further development is needed in order to adapt such a system for real human limb scanning, such as longer robot reach, human safety measures, improved supports.

Keywords: 3D scanning automation, 3D model accuracy, laser triangulation.

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