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## Satisfaction with Customizable 3D-Printed Finger Orthoses Compared to Commercial SilverRing™ Splints

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# Satisfaction with Customizable 3D-Printed Finger Orthoses Compared to Commercial SilverRing™ Splints

## Abstract

*Background:* Emerging research primarily supports 3D-printing as a customizable, replicable orthosis option. However, more research emphasizing orthotic users' viewpoints is necessary to address challenges with orthotic wear adherence and satisfaction.

*Method:* Forty persons were recruited at an academic medical center. After wearing each orthosis for 8 hr (or as long as tolerated), the participants completed post-satisfaction surveys to measure satisfaction with different aspects of both orthoses worn.

*Results:* Forty participants (21 females, 19 males, mean age = 24.98 years) were enrolled in the study. Satisfaction scores (N = 40) were not statistically significant for 3D-printed orthoses compared to SilverRing™ Splints across all domains except for Affordability, which was rated significantly higher for 3D-printed orthoses (M = 10.00, SD = 0.000) compared to SilverRing™ Splints (M = 5.28, SD = 2.35),  $t(39) = 12.70$ ,  $p < .001$ . The mean difference in satisfaction scores was 4.72, with a 95% confidence interval ranging from 3.97 to 5.48.

*Conclusion:* Findings provide novel evidence supporting the use of this customizable 3D-printed prototype as a cost-effective, alternative option to established commercial finger orthoses. This study has potential to assist clinicians' decision-making as they navigate best orthoses options for individuals with swan-neck deformities.

## Comments

The authors declare that they have no competing financial, professional, or personal interest that might have influenced the performance or presentation of the work described in this manuscript.

## Keywords

3D-printing, technology, swan-neck deformity, orthoses

## Cover Page Footnote

Research was conducted at Rush University Medical Center in the Occupational Therapy Academics Department. We thank Jesse Garris of SilverRing™ Splint Company for donating use of splints and a measuring kit, Jeff Canar of Rush University for providing statistical guidance, Abby Paterson of Loughborough University for providing 3D-printed splints education, Hadassah Rosen of Northwestern Medicine for providing conventional splints education, and the students who participated in the study.

## Credentials Display

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Rheumatoid arthritis, an inflammatory, chronic autoimmune condition affecting 1.3 million adults in the United States, can cause social isolation, hinder performance in meaningful occupations, and impact individuals physically and emotionally (Bertin et al., 2016; Siegel et al., 2017). Up to 90% of individuals with rheumatoid arthritis experience a progression of joint pain and disabling hand deformities (Porter & Brittain, 2012). These physical symptoms regularly have a psychological effects on individuals that typically go unnoticed or unrecognized during medical treatment (Margaretten et al., 2011). One specific hand condition often experienced by individuals with rheumatoid arthritis is swan neck finger deformity, characterized by hyperextension of the proximal interphalangeal joint (PIPJ), flexion of the distal interphalangeal joint, and sometimes flexion at the metacarpophalangeal joint (Portnoy et al., 2020). Swan neck deformities can contribute to comorbid major depressive disorder impacting 42% of individuals with rheumatoid arthritis, 2 to 4 times that of the general population (Margaretten et al., 2011).

While anti-swan neck orthoses can limit the progression of the deformity and improve functional performance (Portnoy et al., 2020), an individual's nonadherence to wearing orthoses as prescribed can compromise its effectiveness (Pyatt et al., 2019). Orthosis compliance ranges from 25% to 65% for those with rheumatoid arthritis (Kumari & Saharawat, 2020). It has been attributed to negative social reactions, negative feelings, poor aesthetics, bulkiness, and/or practical orthosis issues (Pyatt et al., 2019). Orthotic users commonly noted that their ideal future orthosis would be visually attractive, discrete, and/or match their outfit (Pyatt et al., 2019). Research suggests that orthotic designs, focused on psychosocial and functional factors, could holistically improve individuals' orthosis wear compliance, performance in meaningful occupations, and overall physical and mental well-being. In addition, because psychological stress exacerbates the immune system's inflammatory response that fuels joint damage and pain in individuals with rheumatoid arthritis (Arthritis Foundation, n.d.), wearing visually attractive orthoses long-term that enhance psychosocial experiences could decrease individuals' stress and contribute to reduced rheumatoid arthritis symptoms.

The SilverRing™ Splint Company, founded by an occupational therapist with a rheumatoid arthritis diagnosis, spearheaded the creation of visually attractive, medically effective finger orthoses to promote positive self-image, enhance holistic well-being, and increase orthosis compliance. The company has focused on designing high-quality, custom-fit ring orthoses in sterling silver and gold (SilverRing™ Splint Company, 2021a). Research on SilverRing™ Splints has focused primarily on the functionality of the orthosis with evidence supporting its ability to improve dexterity and grip strength and reduce dexterity-related pain and PIPJ hyperextension for rheumatoid hand deformities (Spicka et al., 2009; Van Der Giesen et al., 2009; Zijlstra et al., 2004).

Recently, three-dimensional (3D) printing has emerged in clinical practice as a customizable, replicable, and cost-effective option with the potential to promote client compliance (Hunzeker & Ozellie, 2021; Matthews-Brownell & Hall, 2018; Schwartz, 2018). While 3D printing in therapy has primarily focused on adaptive equipment and prosthetics, it is emerging as an orthotic treatment option targeting the areas causing noncompliance (Pyatt et al., 2019). Novel research has found that 3D-printed orthoses are easily replicated using computerized templates if clients lose or break theirs (Matthews-Brownell & Hall, 2018) and that finger orthoses can be fabricated faster than conventional techniques (Sari et al., 2020). 3D-printed orthotic technology can also mitigate fiscal issues for therapists and clients whose insurance may not cover multiple orthoses (Sari et al., 2020). Research has also shown that orthotic makers reported more satisfaction with the fit, aesthetic, process, and orthosis itself for 3D-printed anti-swan neck orthoses

compared to fabricated manually-made orthoses (Portnoy et al., 2020). Furthermore, researchers perceived 3D-printed anti-swan neck orthoses created using a 3D motion scanner as easy to don and doff, inexpensive, easily produced, comfortable, faster to make, and more visually pleasing than conventional orthoses (Sari et al., 2020).

Previous research has primarily focused on comparing 3D-printed orthoses to conventionally made orthoses from the perspectives of clinicians and engineers. However, there are no known studies investigating customizable 3D-printed finger orthoses compared to commercial finger orthoses from orthotic users' perspectives. Therefore, this study aimed to (a) identify a visually attractive 3D-printed orthosis design that can be adjusted and customized and manufactured quickly, easily, and cost-effectively and (b) assess orthotic users' satisfaction with customizable 3D-printed finger orthoses compared to commercial SilverRing™ Splints.

The results of this study have potential implications for improving clinicians' informed decision-making on appropriate devices, increasing client satisfaction and orthotic wear compliance, and allowing clients to be equal decision-makers in treatment processes.

## Method

### Design and Participants

This study had an intra-subject, cross-sectional design. The study received institutional review board approval from the affiliated institution, and 40 participants were recruited at an academic medical center in the United States. Participants were recruited in person on campus and via email. Participants were eligible for the study if they were enrolled at the academic medical center, fluent in English, 18 years of age or older, and with no pre-existing upper-extremity medical conditions. Healthy participants were selected for this study to investigate safety and tolerance without the influence of medical conditions for a novel orthotic design (Karakunnel et al., 2018).

### Quantitative Measures

To assess satisfaction outcomes, the authors asked the participants to complete post satisfaction surveys via SurveyMonkey (SurveyMonkey, n.d.), a HIPAA-compliant survey software. The 3D-printed orthosis and SilverRing™ Splint surveys both contained 19 items with 15 items using a 5-point Likert scale, where score points ranged from (1) *strongly disagree* to (5) *strongly agree*. The surveys were influenced by items on the Orthotics Prosthetics Users' Survey (OPUS): Client Satisfaction with Devices (CSD) and Services (CSS). Person Separation Index has adequate internal consistency (Cronbach's alpha = 0.78 for CSD, 0.74 for CSS), and Item Separation Index has excellent internal consistency (Cronbach's alpha = 0.86 for CSD, 0.82 for CSS) (Heinemann et al., 2003; n = 164). The cost of the 3D-printed finger orthosis prototype at ~\$0.10 and SilverRing™ swan neck orthosis at ~\$94.00 (SilverRing™ Splint Company, 2021c) were included under survey items addressing satisfaction with affordability.

Non-scored survey items 16–19 addressed the duration of time the orthosis was worn, gender, randomly assigned identification number, and an optional comments question. The altered version of the OPUS: CSD and CSS was piloted with a panel of experts. Based on feedback from the panel, modifications to survey questions were made as needed, and the final versions were distributed to the participants.

The 15 survey items were categorized into six domains: Fit and Usability, Skin and Clothing Factors, Physical Features, Psychosocial Aspects, Affordability, and Recommend. Each domain had 15

points possible, except for Affordability (10 points possible) and Recommend (5 points possible). See Table 1 for domain itemizations.

### Procedure

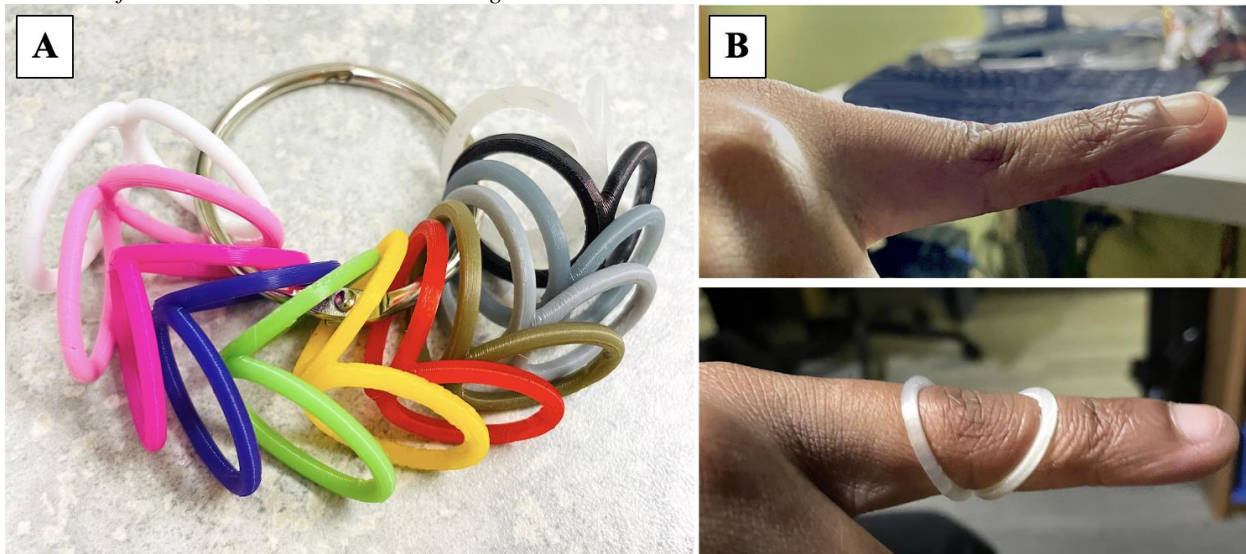
The participants were assigned to wear a 3D-printed finger orthosis and SilverRing™ Splint for 8 hr each on two separate days during their daytime routine. The participants attended an informational meeting where they were provided an overview of orthoses (e.g., features and costs), signed informed consent forms, completed background information forms, provided index finger measurements, and selected color preference from a 12-color palette for a 3D-printed orthosis (see Figure 1).

### Measurement and Production Process

**3D-Printed Finger Orthoses.** The author investigated and developed a novel 3D-printed anti-swan neck orthotic design using Autodesk Fusion 360 computer-aided design software (Autodesk Fusion 360, 2021). Six orthosis fitting trials were performed to ensure measurement accuracy for the study. The prototype was inspected and approved as a functional anti-swan neck orthosis (see Figure 1) by an expert certified hand therapist with over 3 decades of hand therapy and occupational therapy experience.

**Figure 1**

*Features of the Customizable 3D-Printed Finger Orthosis*



*Note.* Image A: 12-color palette for customization. Image B: Orthosis functionally blocking proximal interphalangeal joint (PIPJ) hyperextension.

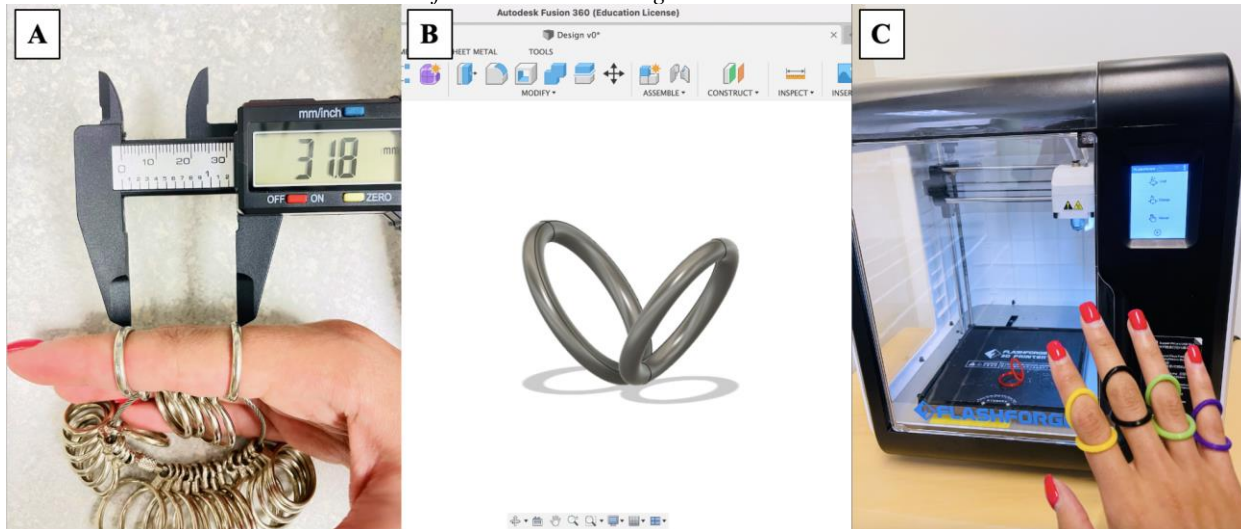
The participants' index fingers were measured both proximally and distally to PIPJ using a ring sizer gauge tool. The two recorded ring sizes were then converted to diameter lengths for upcoming software design steps. To determine the accurate length of the orthoses, a digital caliper was used to measure the distance between the midpoints of the proximal and middle dorsal phalanxes (see Figure 2). The time duration of measurement ranged from 2 to 4 min per participant. Based on the measurements, the predesigned orthosis prototype was modified to each participant's index finger using Autodesk Fusion 360 (see Figure 2).

The final models were then converted into files using FlashPrint slicing software (FlashForge 3D Printer, 2021a) and uploaded to Flashforge Adventurer 3 3D printers (FlashForge 3D Printer, 2021a). The orthoses were then manufactured from multicolored polylactic acid (PLA) filaments (FlashForge 3D Printer, 2021b) based on each participant's color preference (Figure 2). Each orthosis took 14–16 min to

design and print, and the estimated cost was ~\$0.10 using the following equation:  $\$ x / \text{Estimated Material (m)} = \$34 / 166.5 \text{ m}$  (Hunzeker & Ozellie, 2021). The additional costs for 3D-printed and commercial devices, in terms of labor, machinery, training, and time, were not considered in this analysis (Hunzeker & Ozellie, 2021).

**Figure 2**

*Measurement and Production Process of the 3D-Printed Finger Orthosis*



Note. Image A: Orthosis fitting. Image B: Designing orthosis based on measurements. Image C: Multicolored orthoses and 3D-printer.

**Commercial SilverRing™ Splints.** The SilverRing™ Splint Company donated the orthoses and measuring kit for the study. The author performed six orthosis fitting trials to ensure measurement accuracy for the study. The participants were sized for orthoses according to the manufacturer's measuring instructions (SilverRing™ Splint Company, 2021b). The time duration of measurement ranged from 4–7 min per participant. Appropriate orthosis sizes were then ordered, manufactured, and delivered within 6 business days.

Once both orthoses were finalized, the participants attended an orthosis fitting to ensure safe and proper sizing. For the participants whose 3D-printed orthosis fit improperly, new orthoses tailored to updated finger measurements were printed and provided. For the participants whose SilverRing™ Splints fit improperly, the malleable orthosis was adjusted to an appropriate size, and the participants were educated on how to adjust these orthoses throughout the day as needed. The participant responsibilities were verbalized, and the participants were educated and demonstrated safe donning/doffing of both orthoses. The participants were advised to discontinue wearing either orthosis should they experience any physical or mental distress during its application. Orthoses were provided in plastic bags that also contained each participant's randomly assigned identification number required for the post-surveys. The participants then received an email with study guidelines and the two post satisfaction survey links.

All 40 of the participants wore one of the finger orthoses for 8 hr during their regular daytime routine (or as long as they could tolerate), completed a post satisfaction survey on the experience, and on the following day performed the same tasks for the second orthosis. Upon completion of the study, the participants returned SilverRing™ Splints to the author and were able to keep their customized 3D-printed orthoses.

## Data Analysis

Statistical analyses were performed using IBM SPSS Statistics (Version 25.0; IBM Corp., Armonk, NY). The difference in satisfaction scores between the two orthoses was analyzed using paired t-tests. To protect from Type I Error, the authors conducted a Bonferroni correction ( $.05/6 = .008$ ). The adjusted statistical significance level using Bonferroni correction was set at  $p < .008$ . For statistically significant differences, 95% confidence intervals were identified.

## Results

### Study Population

Forty of the participants (21 females, 19 males, mean [ $M$ ] age = 24.98 years) were fitted for both orthoses. All of the participants ( $N = 40$ ) wore 3D-printed finger orthoses ( $M = 8.4$  hr) and SilverRing™ Splints ( $M = 8.7$  hr) during their daytime routine on two separate days and completed one post survey per orthosis.

### Orthotic User Satisfaction

Satisfaction scores ( $N = 40$ ) were not statistically significant for 3D-printed finger orthoses compared to SilverRing™ Splints across all domains except for the Affordability domain, which was rated significantly higher for 3D-printed orthoses ( $M = 10.00$ ,  $SD = 0.000$ ) compared to SilverRing™ Splints ( $M = 5.28$ ,  $SD = 2.35$ ),  $t(39) = 12.70$ ,  $p < .001$  (two-tailed). See Table 1 for results for all six domains. The mean difference in satisfaction scores between 3D-printed orthoses and SilverRing™ Splints was 4.72, with a 95% confidence interval ranging from 3.97 to 5.48.

**Table 1**

*Orthotic Users' Satisfaction Scores for 3D-Printed Orthoses and SilverRing™ Splints*

Domain	Satisfaction Survey Item(s)	Points Possible	3D-printed $M$ ( $SD$ )	SilverRing™ $M$ ( $SD$ )	$t(39)$	$p$
<b>1. Fit and Usability</b>	1. Fit 3. Comfort 4. Ease to don	15	13.13 (1.47)	13.18 (1.60)	-0.16	.87
<b>2. Skin and Clothing Factors</b>	7. No clothing wear and tear 8. No abrasions or irritations 9. Pain-free	15	13.88 (1.60)	13.60 (1.78)	0.91	.37
<b>3. Psychosocial Aspects</b>	12. Decision-making partner 13. Confidence 14. Positive social reactions	15	12.75 (1.84)	11.95 (2.15)	2.51	.02
<b>4. Physical Features</b>	2. Weight 5. Aesthetics 6. Durability	15	13.15 (1.53)	13.78 (1.42)	-2.21	.03
<b>5. Affordability</b>	10. Expense 11. Replace and Repair	10	10.00 (0.00)	5.28 (2.35)	<b>12.70</b>	<b>.000*</b>
<b>6. Recommend</b>	15. Recommend to someone with finger condition	5	4.43 (0.71)	4.28 (0.75)	0.85	.40

Note.  $M$  = mean;  $SD$  = standard deviation.

\*Bonferroni corrected  $p < .008$ .

## Discussion

The main findings demonstrate that 3D-printed finger orthoses were comparable to SilverRing™ Splints across all domains except for the Affordability domain, where 3D-printed finger orthoses were favored. Research thus far has primarily focused on comparing 3D-printed orthoses to conventional orthoses and from the perspectives of clinicians and engineers. However, this is the first known study assessing 3D-printed orthoses compared to an established commercial orthotic brand from orthotic users' perspectives. These results provide novel evidence that supports 3D-printed finger orthoses' potential as an alternative, client-centered, cost-effective option to established commercial finger orthoses for individuals with rheumatoid arthritis and/or related finger conditions.

### Domain 1: Fit and Usability

Domain 1, encompassing satisfaction with fit, comfort, and ease to put on, was comparable for both orthoses. This was expected, as the measuring intricacies and discrete design of each orthosis were similar. Before the commencement of the study, rigorous measurement trials were conducted as research supports that orthosis discomfort and nonadherence are caused by poorly fitted orthoses (Pyatt et al., 2019). This, in addition to scheduling orthosis fittings, likely contributed to satisfactory fit experiences for both orthoses. Previous research found that 3D-printed orthoses, compared to conventional casts, were similar in usability (Oud et al., 2021) but received higher comfort scores (Chen et al., 2017, Oud et al., 2021). Although usability scores in the current study were consistent with these previous findings, it is hypothesized that the current study's 3D-printed orthosis did not have higher comfort scores, as it was compared to an established commercial finger orthosis rather than a manually made orthosis. Traditionally fabricated orthoses are molded using plaster and thermoplastic material, creating a rigid structure without flexibility and poor ventilation (Chen et al., 2017). In contrast, the commercial SilverRing™ Splints in this study were established over 25 years ago, have undergone extensive testing, and were manufactured using high-quality, custom-fitted sterling silver (SilverRing™ Splint Company, 2021a). Because the two most important qualities of orthotic devices are considered to be comfortable ( $n = 54$  or 75%) and ease of use ( $n = 53$  or 74%) (Joseph et al., 2018), 3D-printed finger orthoses' comparable satisfaction scores to an established commercial orthosis demonstrate its potential in promoting orthosis compliance.

### Domain 2: Skin and Clothing Factors

Domain 2, encompassing clothing free of wear and tear, no skin abrasions or irritations, and pain-free to wear, showed comparable results for both orthoses. Because of orthoses' small dimensions, wear and tear of clothing likely would be of little to no concern for both orthoses. However, there were a few participant reports that one or both orthoses caused irritation, redness, and/or swelling to the skin intermittently throughout the day. This could be explained by fingers being unaccustomed to wearing a device at their PIPJ. Furthermore, finger swelling in healthy individuals can be triggered by hot weather, causing joint and finger size fluctuations throughout the day (DiGiulio, 2019). This study was conducted during the summer months, and because both orthoses' placements were localized directly around the PIPJ, finger swelling was possible, resulting in intermittent skin sensitivity, orthotic pressure points, and friction. For the majority of the participants who were satisfied with this domain, the lightweight material of the 3D-printed orthosis and the smooth, sterling silver of the SilverRing™ Splint may have contributed to irritation-free experiences. It is recommended that clients who experience frequent swelling fluctuations consider obtaining multiple-sized 3D-printed orthoses or consider the use of a SilverRing™ Splint because of its malleable adjustable size feature.



### **Domain 3: Physical Features**

Domain 3, involving weight, aesthetics, and durability, found no statistically significant difference between the orthoses. It is important to note that specific to durability, the participant reports showed four instances (three males, one female) of 3D-printed orthoses breakage, while the SilverRing™ Splints showed zero instances. The 3D-printed orthoses' plastic material was relatively less durable than the sterling silver used in the construction of SilverRing™ Splints. It is recommended that alternative material and design enhancements should be considered in the future to enhance further the durability of the 3D-printed finger orthoses.

Consideration of the demographics of the orthotic users that reported orthosis breakage should also be explored. Research has found that orthosis nonadherence is seen more in males than females and for those below 27 years of age (Kumari & Saharawat, 2020). The participants' mean age was below 27 years of age, and 75% of the 3D-printed finger orthoses broken were by the participants identified as male. It is inferred that the orthotic user demographic should be a consideration for orthosis negligence. Because there were no breakage instances with SilverRing™ Splints, these orthoses may be a better consideration for clients that are in the demographics more susceptible to orthosis nonadherence.

### **Domain 4: Psychosocial Aspects**

Domain 4, addressing confidence, social reactions, and feeling like a partner in decision-making, was comparable for each orthosis, which is thought to be because of both orthoses' psychosocial considerations. Both orthoses' aesthetical designs were influenced by jewelry, and the participants may have received positive social reactions and increased confidence on both accounts. However, the results showed a near clinical significance in favor of 3D-printed orthoses, likely accounted for by the participants' opportunity to feel like a partner in decision-making when selecting their orthosis' aesthetic from a 12-color palette. Since individuals with rheumatoid arthritis commonly identified negative feelings and social reactions as prime reasons for orthosis nonadherence (Pyatt et al., 2019), high satisfaction ratings in this domain show potential for increased compliance and psychological well-being for 3D-printed finger orthoses.

### **Domain 5: Affordability**

Domain 5, encompassing Affordability with the expense of out-of-pocket and repairs and replacements, showed significantly higher satisfaction for the 3D-printed orthoses. This is likely because of the inexpensive cost of the 3D-printed finger orthosis at ~\$0.10, compared to a SilverRing™ swan neck orthosis at ~\$94.00 (SilverRing™ Splint Company, 2021c). This supports previous research confirming that more cost-effective orthoses demonstrate higher compliance rates, as does a participant report that the expense of the SilverRing™ Splint made them nervous about wearing it because of fear of losing it (Fisk et al., 2016; Ghoseiri & Bahramian, 2012; Joseph et al., 2018). 3D printing's cost-effective nature could be a contributing factor to improved orthosis compliance and serve as an acceptable alternative, cost-effective option to established commercial orthoses.

### **Domain 6: Recommend**

Domain 6, specific to recommending the orthosis to someone with a finger condition, was comparable for both orthoses, which could be because of both orthoses' unique features. The 3D-printed orthosis came in 12 different colors, was cost-effective, and had a lightweight material that some of the participants noted they preferred. For the participants who preferred an attractive orthosis with more durability and adjustable sizing, the SilverRing™ Splint would be the preferred option. Because orthotic

biomechanics and functionality would also be considerations for recommending orthoses to someone with a finger condition, the next phase of research would investigate the effectiveness of this customizable 3D-printed orthosis prototype compared to commercial finger orthoses for individuals with rheumatoid arthritis and/or related finger conditions.

There was a participant report that the 3D-printed orthoses could also serve as an effective option for growing children, who might show increased orthosis nonadherence because of their young age (Kumari & Saharawat, 2020). The younger age group may also prefer the variety of bright-colored options, and parents or guardians would be less concerned about purchasing a new orthosis because of their child growing out of it or losing/breaking theirs as a result of its cost-effective nature. 3D-printed finger orthoses may have future potential for pediatric clients diagnosed with juvenile rheumatoid arthritis and/or related finger conditions.

### **Additional Considerations**

While this study focused on orthotic user satisfaction, the authors noted significant benefits to measurement and production time for 3D-printed finger orthoses. Measurements for 3D-printed orthoses took 2 to 4 min and production time for each orthosis took 14 to 16 min. SilverRing™ Splint measurements were double that duration at 4 to 7 min and took 6 business days to be ordered, manufactured, and delivered. Further research investigating clinicians' perspectives on this for both orthoses would be recommended and warranted to assist decision-making on the use of 3D-printed orthoses in practice.

### **Limitations**

The sample size was small, and the participants all belonged to a similar demographic, limiting the generalizability of this study to the greater population. Because of using healthy participants, evidence of how biomechanically and functionally effective 3D-printed orthoses are could not be assessed. Bias could have also occurred as the participants may have underlying interests in emerging medical technologies. Finally, the current study analyzes only the short-term use of the orthoses when they function primarily for permanent use, limiting its feasibility as a long-term option.

### **Conclusion**

This study aimed to compare customizable 3D-printed finger orthoses to established commercial finger orthoses from orthotic users' perspectives. This article provides novel findings supporting the use of customizable 3D-printed finger orthoses as an alternative, client-centered, cost-effective option to commercially available finger orthoses. The findings of this study may assist clinicians' decision-making as they navigate the best orthotic treatment option for individuals with rheumatoid arthritis and/or related finger conditions. 3D-printed finger orthoses may increase client satisfaction and orthosis compliance and allow clients to be equal decision-makers in treatment processes.

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