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A NOVEL MODEL FOR THE MATERIAL SELECTION OF SMART OBJECTS FOR HAND-REHABILITATION: A CASE STUDY

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ABSTRACT

Home hand rehabilitation for stroke is becoming increasingly important due to logistic and financial challenges. Developing Daily-life Integrated Hand-rehabilitation Products (DIHP) aims to enable the application of at-home rehabilitation. The materials of these products are essential for their success, however, selecting materials for DIHP has not been investigated yet. Previous research on material selection showed that it is done strictly on material properties or based on a human-centered approach. Hence, in this study, we propose a hybrid model for choosing materials for DIHP. To achieve this, we first combined the findings of previous material selection processes into a comprehensive material selection model. We applied this model in a case study, in which we first selected three materials based on their properties. Following, we 3d printed a DIHP out of the chosen materials and tested the feeling of the materials with multiple expert groups. Our findings suggest that the proposed material selection method is promising and highlights that our comprehensive model provides more insights when compared to a strict material property-based selection.

Keywords: Home Rehabilitation, Material Selection, Case study, User centred design, 3D printing

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1 INTRODUCTION

Stroke is one of the leading causes of hand and arm disability worldwide (Coleman *et al.*, 2017; Sennfält *et al.*, 2019; Virani *et al.*, 2020). Besides, one in two people recovering from a stroke has an altered touch sensation (Goodin *et al.*, 2018). Physiotherapy in rehabilitation centres helps patients regain their hand functionality and prevents loss of hand functions. Still, one-third of the patients lose the range of hand motion six months after stroke (Kwah *et al.*, 2012), and over 50% of the recovering patients do not regain their hand functions (Kwah and Herbert, 2016). One reason for such loss is that even though they are required to, patients stop doing the therapy exercises at home.

Various interactive conceptual products have been developed to address this problem. Some of these are game and functionality based (e.g., Smart Boards (Park *et al.*, 2018) and wearable gloves (Friedman et al., 2014)) products, while some of them tackle incorporating the activities of daily living into at-home hand rehabilitation (e.g., eating (Stefess et al., 2022)) and drinking activities Hover et al.,2023). However, even though very promising, such concepts are far from further implementation due to several challenges. In this paper, we will address one of them: material selection.

Materials, in addition to the functions and aesthetics, affect the success of products(Edwards, 2013; Ljungberg and Edwards, 2003). Therefore, three approaches were developed to facilitate the material selection process in consumer product development: (1) property-based (such as yield strength and melting point of a material) (Ashby, 2010; Sandström, 1985), (2) feel-based (such as associating or feeling)(Larson, 2015) and (3) a combination of property-and-feel-based(Edwards, 2013). Still, material selection has its own challenges: it is often regarded as complex, complicated, and difficult to follow (Brechet *et al.*, 2001). On top of these, designers should be even more tedious in material selection for Daily-Life-Integrated Hand Rehabilitation Products (DIHP), as selecting proper materials for DIHP will affect the success of hand rehabilitation exercises. Furthermore, due to their novelty and difference from existing products, no model facilitates material selection for DIHP.

Therefore, this paper proposes a novel and easy-to-follow material selection model for DIHP. In the following lines, we explain the related work we build on. We present the model we developed for selecting materials for DIHP and provide the early evaluation results to validate the model. We aim to answer the following research question *"How can the property-based material selection be effectively combined with human-based material selection to select materials for hand rehabilitation products."* In the following lines, we will explain both approaches that guided us in developing our model. We then conclude our paper with directions for future work.

2 RELATED WORK

2.1 Property-based material selection

One of the highest renowned material selection methods in the literature is Ashby's material selection method, which has four steps for choosing a feasible material (Ashby *et al.*, 2019). Accordingly, material selection starts with translating the user-set material requirements into functionality requirements such as constraints, objectives, and free variables. After defining the functionality, constraints can be set. The constraints must be set to achieve the function with the geometric constraints adequately. These can also be seen as non-negotiable conditions that must be met. After determining the constraints and objective, the designer can screen the materials. In this final step, all materials that do not fit the essential constraints are eliminated from the selection—leaving the designer with a list of materials which each should be able to make a functional product. After determining this list of materials, the following step is ranking the objectives to determine which screened materials can be best used (Ashby *et al.*, 2019). With this completed, the final step is to document the research of the top-ranked materials.

In property-based material selection, the selection is made with a limited analysis of alternatives. For example, it poses limitations caused by the designer's biases and (in)experience. This brings the risk of selecting materials without a structured method. The choice of material is often based on materials of

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similar designs to the product or materials familiar to the designer (Sandström, 1985). Another disadvantage of selecting materials solely on their material properties (such as fracture toughness, melting temperature, and waterproofness) is that it misses the human aspect, which can cause a product to miss the user's preference (Larson, 2015).

Some sources argue that simplifying the selection process by focusing solely on property-based requirements leads to mediocre products (Ljungberg and Edwards, 2003). When solely focussing on property-based requirements, non-technical requirements are often overlooked(Edwards, 2013). This poses a problem when material selection contributes to the experience and the use of rehabilitation products. A reduction in the time the patient spends on rehabilitation could lead to decreased long-term hand mobility (Langhorne *et al.*, 2009). Therefore, the product materials should be decided upon in a unified process, including user-focussed industrial design requirements (Edwards, 2013; Farag, 2013; Ulricht and Eppinger, 2004).

2.2 Human-centred material selection

In *Material Selection Based on Feel*, a structured approach was provided to select materials based on qualitative, human-centred requirements (Larson, 2015). Rather than looking at the constrain requirements as a number that must match a predefined threshold (Jahan and Edwards, 2013), material selection was compared to a point of reference (Edwards, 2013; Larson, 2015) determined by a human-centred approach that defines the subjective value of whether a material feels "just right" (Larson, 2015).

To rate the different materials and select the most suitable materials for a product, the designer should form and use a so-called 'feel team,' a group of selected experts who rate pre-selected materials (Larson, 2015). Accordingly, such pre-selection can be done by consulting databases or material experts. Once a feel team has been assembled, a designer specifies the desired and essential material aspects relevant to the product's expected to feel.

After the initial list of materials was compiled, the feel-experts teams arranged for material test samples (i.e., swatches) to be analysed. Based on the expert evaluation, we then further analysed the top-selected materials. This way, the prototypes the feel team should test again should be further produced. The last step in the process is to decide on the final material based on the feel team's opinion. Based on this decision, a final prototype can be made.

2.3 Combination of human-centred and property-based selection approaches

Even though there is an emphasis on employing a combination of human-centred and property-based selection approaches for the success of products, only one study reported the combination of human-centred and property-based material selection requirements (Piselli *et al.*, 2016). In that study, the human-centred aspects are measured at a basic level using the "Napping® Test", a test that uses square patches of materials to be felt by experts, after which the sensory profile of specific materials is created (Faucheu *et al.*, 2015; Piselli *et al.*, 2016). Other research (Larson, 2015), however, indicates that a more product-specific investigation needs to be conducted on materials to understand the feasibility of the materials for different products. Simplifying the material selection process in such a fashion can cause the developed product to miss the user's preference (Larson, 2015). Such an approach is necessary for product development and DIHP, as these products can enormously benefit from the human-centred and property-based material selection.

3 A HYBRID MATERIAL SELECTION MODEL FOR DIHP

Based on the key takeaways of the literature (the steps taken in the property-based material selection and the actions taken in the human-centred material selection), we developed a material selection model to be used in the design process of DIHP (Figure 1). We propose that the first step of the material selection process should be to arrive at well-defined design requirements (Ashby *et al.*, 2019; Edwards, 2013; Sandström, 1985). These requirements could then be compared against material properties from existing databases. The second step should be to differentiate the requirements to be attained into constraint requirements and objectives requirements (such as cost and weight) (Ashby *et al.*, 2019; Sandström, 1985). To achieve this, the designers should screen the possible materials and eliminate those not

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complying with requirements. The filtered list of materials then needs to be compared and ranked against each other. Finally, when multiple optimizable requirements are equally crucial for the final material choice, the selection of optimal materials is attained by finding the Pareto optimum. This is a selection method that graphs multiple requirements at once against each other, and gives an optimal curve on which the optimal points of these requirements lie (Jahan and Edwards, 2013).

Based on user preferences, a material can be selected from the material on the Pareto curve. Lastly, once a selection has been made based on the initial screening, to ensure the users have the best experience with the product, a so-called 'feel team' (as defined in (Larson, 2015)) is put together. This feels team analyses a select list of materials based on personal, physical, and emotional requirements on how they feel. This is conducted to ensure the product is made of a material people feel good about (Larson, 2015). When products are not up to par with a selected material, the problem needs to be identified by **the researcher** based on the results of the feel team to find whether the problem lies in the post-processing of the product (Gibson *et al.*, 2015), requirement limitations (Larson, 2015), or the design of the product itself. When the product is up to par with property-based and human-centred requirements, the material can be used as an option for the DIHP. From the final selection of materials, a choice could be made by ranking the materials again against the objectives of the products (for instance, as economical as possible) and choosing the top material. If no material can be selected at the end of the selection cycle, a revision is required in the requirements set or the product's design.

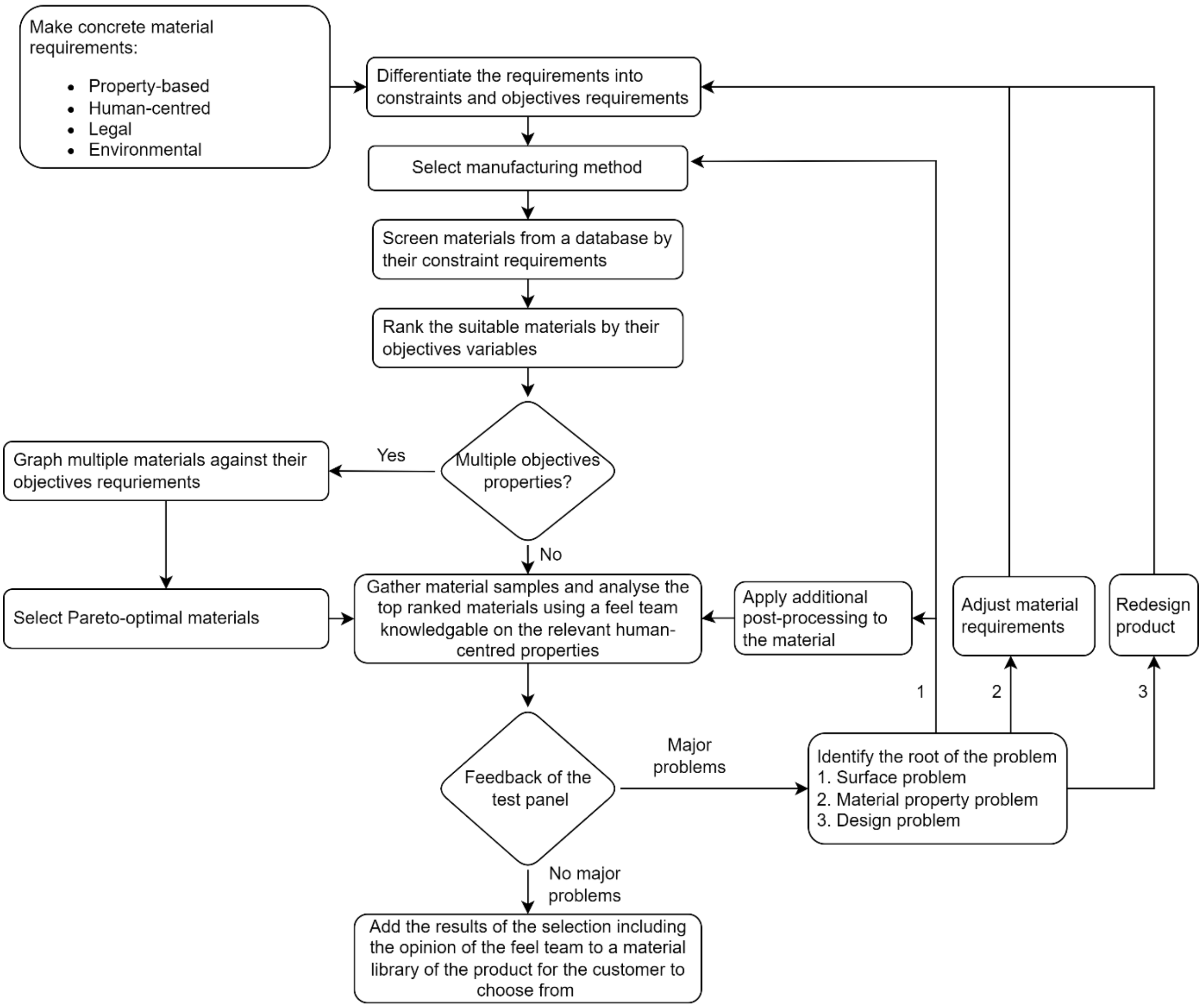

Figure 1: Our proposed novel material selection model for DIHP

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4 TESTING THE HYBRID MATERIAL SELECTION MODEL FOR DIHP

We employed our previously published related work to test the hybrid material selection model for DIHP (Stefess *et al.*, 2022). Gr!pp is an add-on grip for helping stroke patients practice certain grasps. Our current paper is a follow-up and independent of our prior work. We used the form of Gr!pp to test the applicability of the approach we explained in Figure 1. In the following lines, we will explain the results of applying our material selection approach.

4.1 Property-based material selection

First, we set material requirements based on the contextual factors that play a role in the use of Gr!pp, like the working conditions (e.g., kitchen). We then 3D-printed several prototypes based on a set of pre-set material requirements. These were material strength (i.e., strong enough not to break when used in the kitchen), fracture toughness (i.e., should not break when falling from 1.5m height), glass-and melting temperature (i.e., should not melt above a boiling pan) and (non-) toxicity (i.e., shall be non-toxic).

Table 1 shows the data retrieved from a comprehensive material database (ANSYS inc., 2022) and the selection of materials that fit the material requirements. This database was selected due to its usability and comprehensive inclusion of requirements. The first column shows the name of the material, and the following columns show the properties. The arrow behind the property shows whether the minimization (↓) or maximization (↑) of this specific property is desired. Outliers in this table are GFRP and CFRP, which are expensive and heavy. CFRP also has a notably high CO_2 footprint. Furthermore, Nylon has a relatively low glass temperature, which means it is prone to deformation when heated.

Table 1: Property-based material selection

Material	**Price ↓ (€/kg)**	**Density ↓ (kg/m³)**	**Fracture toughness ↑ (MPa×m0,5)**	**Glass temperature ↑ (°C)**	**CO_2 footprint primary production ↓ (kg/kg)**
Polyethylene terephthalate (PET)	0,88	1290	4,75 - 5,25	59,90 - 83,90	2,59
Polyvinylchloride (tpPVC)	0,92	1290	3,63 - 3,85	79,90 - 87,90	2,57
Acrylonitrile butadiene styrene (ABS)	1,46	1030	1,46 - 4,49	102 - 115	3,27
Polymethyl methacrylate (PMMA)	1,53	1170	0,70 - 1,69	99,90 - 110	4,64
Polyester (UP)	1,62	1040	1,09 - 1,69	150 - 210	2,41
Phenolics (PH)	1,69	1240	0,787 - 1,21	170 - 270	1,77
Polycarbonate (PC)	2,10	1190	2,10 - 2,30	142 - 158	4,53
Cellulose polymers (CA)	3,00	980	1,50 - 1,80	103 - 111	3,24
Polyamides (Nylon)	3,73	1120	3,00 - 4,00	**44 - 66**	6,09
Glass Fibre Reinforced Polymer (GFRP)	**28,70**	1750	19,30 - 31,00	99,90 - 180	5,88
Carbon Fibre Reinforced Polymer (CFRP)	**32,40**	1500	6,12 - 20,00	99,90 - 180	**45,80**

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After coming up with an initial list of materials that conform with the property-based requirements, as seen in table 1: property-based material selection, we made a final selection to evaluate human-centered aspects. Based on available resources and our intention to use 3D printing, we chose PH, Nylon, and ABS(+) for this selection.

4.2 Evaluation of material selection model

To find human-centred insights into the materials, we formed feel teams. The goal of the human-centered selection phase is to find out whether there are any major problems with the materials in the list, filter out these materials, or find the root of these problems to resolve. By filtering out unfit materials or resolving root problems, a better material can be chosen, which, as described in the literature, will cause the product to be more successful (Larson, 2015). The experimental protocol was approved by the ethics committee of our research institute before the experiment.

4.2.1 Participant selection for the feel-team

When comparing products based on feel, it is vital to have a group of participants who can express their opinion on the different feel aspects of the product (Larson, 2015). Because stroke patients' senses of touch strongly vary, results from a small group may not be objective or representative of the majority. Therefore, the initial testing used field experts rather than selecting a representative group of stroke survivors. Based on these, we formed a feel-team that consisted of people who knew the needs of the stroke patients and knew the limitations and restraints of specific material choices but excluded the target users of the DIHP. We identified three fields of expertise for material selection based on their connection to the development of DIHP: physiotherapists, designers, and material science experts. We contacted the potential feel-team participants via e-mail and informed them about the experimental protocol in advance.

We recruited nine participants for domain-specific feel-teams: three physiotherapists, three designers, and three material scientists. We recruited experienced physiotherapists, each with over 20 years of experience in their field and expert in recovery after stroke. We recruited material science experts due to their expertise in different material properties. Lastly, we recruited designers due to their expertise in connecting design choices with material choices.

4.2.2 Study protocol

First, a CAD model of the Gr!pp was made. After that, a prototype was 3D printed for each of the three selected materials using the CAD-generated STL file (Figure 2: Prototypes. Materials from left to right, Nylon, PH, ABS+). The nylon prototype was made using SLS printing, the PH prototype using vat polymerization, and ABS+ using FDM printing. After making the prototypes, the participants of the feel-team each were invited to a discipline-specific focus group (3 different focus groups), to get discipline-specific insights and to avoid discussion between the different disciplines. In these focus groups, the materials were physically tested. The goal of the focus groups was to gain insights into the user-centred requirements and to find out whether the chosen materials contained any severe flaws from a user-focused aspect. First, we asked the participants for their informed consent. All participants signed a form agreeing their data could be used.

Figure 2: Prototypes; materials from left to right, Nylon, PH, ABS+

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Following, we presented the 3D prototypes, which are different material versions of the Gr!pp (Stefess *et al.*, 2022). We asked the participants to rate the prototypes on 12 statements indicated on a material selection form on a 5-point Likert scale (1=fully disagree, 5=fully agree) and how important they deem the statements on a 3-point Likert scale (1= not important, 3= very important). These statements and their scores can be found in Table 2. At the end of the analysis of the feel team, we asked the participants questions regarding their expertise. The responses were recorded and filled in on the professional expertise form, after which they were used as insights for the discussion of this research. The sessions took about 30 minutes.

4.2.3 Data analysis

For the input of the feel team, descriptive statistics such as the mean and standard deviation of the 5-point Likert rankings were given to the different aspects of the materials. These values were processed to understand the preferences between the participants. Based on the implied importance of the feel teams, a weighted ranking has been made, after which the most prominent material has been selected. Next to the weighted ranking (based on the deemed importance given by the participants on the statements as described in table 2), the data has also been plotted in an importance-performance matrix. This was made to understand the flaws in the different materials and the points of attention.

4.3 Results

As indicated before, three materials (ABS+, PH (Resin), and Nylon) have been analysed by feel teams. Results showed that (Table 2) that Nylon scores above average except for the tactile points, ABS scores significantly below average on all statements, and PH scores above average, except for the smell of the material, which has been indicated to be a severe downside of the material.

Table 2: Results of the feel teams

			Physiotherapists			**Designers**			**Material scientists**		
		PI*	ABS+	PH	Nylon	ABS+	PH	Nylon	ABS+	PH	Nylon
1	The material feels authentic	2,37	2,66	3,66	4,33	2,66	3,66	3,66	2,83	3,83	2,33
2	The material feels reliable	2,90	3,66	4,33	4,33	3,66	4,33	3,33	2,00	5,00	2,66
3	The material has a good grip	2,83	2,33	3,66	3,66	2,33	3,66	4,00	2,33	4,00	3,66
4	The material looks attractive to use	1,97	3,66	3,33	3,66	3,66	3,33	3,00	2,33	1,33	1,00
5	The product has a comfortable mass to use	2,30	4,33	3,66	3,66	4,33	3,66	4,33	2,00	4,00	3,00
6	The product temperature feels comfortable to hold in hand.	1,70	3,33	3,66	4,66	3,33	3,66	3,33	4,33	4,66	4,66
7	The contact pressure of the product feels comfortable	2,37	3,00	3,66	3,00	3,00	3,66	2,33	2,66	3,00	3,00
8	The material feels ergonomically pleasing	2,73	2,33	3,66	3,00	2,33	3,66	3,33	2,00	3,33	2,00

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		PI*	Physiotherapists			Designers			Material scientists		
			ABS+	PH	Nylon	ABS+	PH	Nylon	ABS+	PH	Nylon
9	The product does not make any undesired movements	1,70	4,33	4,33	4,33	4,33	4,33	4,33	5,00	5,00	5,00
10	The product does not emit a notable odor	2,67	5,00	1,00	5,00	5,00	1,00	5,00	5,00	2,00	5,00
11	I am willing to pay for this product	1,93	3,66	3,66	3,66	3,66	3,66	3,66	2,00	1,66	2,33
12	The material seems innovative	1,03	3,33	3,66	3,33	3,33	3,66	4,33	1,66	1,33	1,66

Scores are on a 5-point Likert Scale. 1 = do not agree, 5 = fully agree
**Perceived Importance. 1 = not important, 3 = very important*

After data collection, a weighted ranking was done on the statements in Table 2. The value of the weighted ranking was based on the perceived importance of the statements (PI in table 2). For this, the mean value of the rating given on the statement by the participants is multiplied by the perceived importance of the statement. This gives a mean weighted value per statement. By summating the weighted values of each statement, a score can be given to the materials. For example, looking at statement 1 for ABS+, the PI is 2,37. the average score on statement 1 for ABS+ is 2,72 when combining the three focus groups. Multiplying 2,37 and 2,72 gives a weighted value for statement 1 of ABS+ of 6,44. After summating all weighted values of all 12 statements, ABS+ scored 80 points, PH 89, and Nylon 94 points, indicating Nylon to be the favourite material of the feel team and ABS+ the least favourite.

Based on the results, we charted the importance/performance matrix for each question in Table 2 and for each participant group. Figure 3 shows this importance-performance matrix. The x-axis shows how important the participants perceived the statements to be. The y-axis shows the score given by the feel team.
The bottom right quadrant is perceived as important and shows the statements of the different materials which are negatively perceived. This quadrant shows the parts of the material that urgently need to be improved for the material to be feasible. A strong outlier, for instance, is statement 10 from PH, which is the smell of the material. For this material to be considered for the final product, the odour needs to be solved. All in all, it can be seen that Nylon has two issues to be resolved, PH 3 and ABS+ 7. This matches the previously found scores that ABS+ was perceived as least favourable by the feel team.

5 DISCUSSION

In this study, we looked into how property-based material selection can be effectively combined with human-based material selection to select materials for hand rehabilitation products. Based on literature findings and interviews with experts, a hybrid model has been constructed, which shows a step-by-step approach to selecting materials with both aspects considered. Furthermore, a case study has been conducted that tested the model on a real-life DIHP. Our material selection model has been tested on a DIHP, for which we hypothesized that it is important to have a human-centred material selection process due to the close human interaction with the product. The results gave us many interesting insights into how important the human aspect is. For example, PH did not score well for highly important question 10; both Nylon and ABS+ did not score well for question 8, and PH scored relatedly worse than Nylon and ABS+ for question 10.

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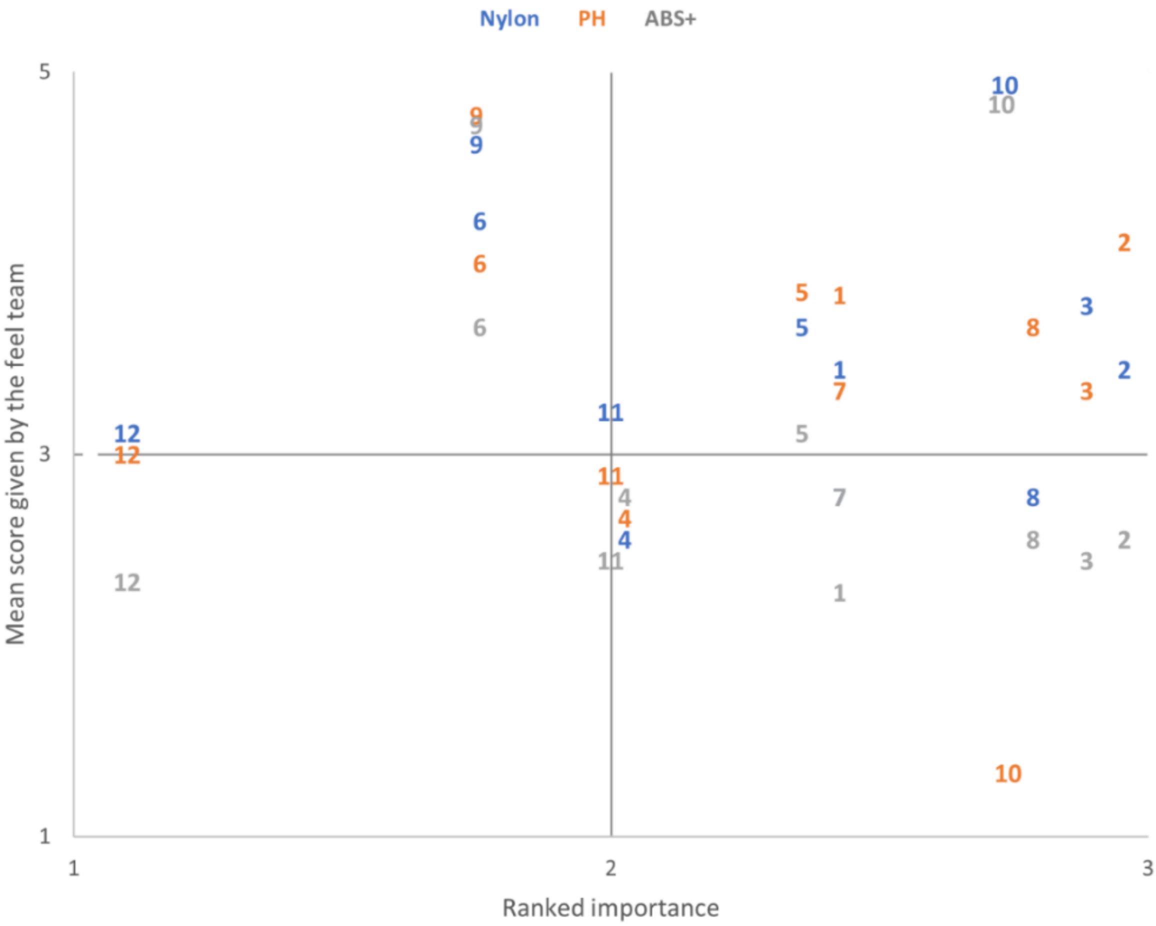

Figure 3: Performance plotted against the ranked importance given by the feel team based on their mean Likert score for each of the 12 statements. The numbers indicate the specific statements, the y-axis is the mean score given to this statement, and the x-axis is the perceived importance of each statement. Top-left quadrant, high-rated, low-importance; top-right quadrant, high-rated, high importance; bottom left quadrant, low-rated, low-importance; bottom-right, low-rated, high-importance.

This matrix gives a direct overview of the suitability of the material for DIHPs. Suppose many of the important human aspect points are sub-par. Then, the material needs to be revised upon those points before it can be used as a material for DIHPs because lacking these aspects would hinder the success of the products. Even though, for example, ABS initially seemed like the best option as a material for the Gr!pp due to its excellent strength, ease of printing, and favourable price and density. It showed severe flaws in human-centred research. These flaws must be addressed before the material can be used for the DIHP. Based on human preference, the results show Nylon to be the favourite. These results seem to confirm previous research findings (Edwards, 2013) that the combination of property-based and human-centred material selection has merit for proper material selection. By integrating this model into the design process for such products, it is expected to have a better material choice, which in turn would give a product (Ljungberg and Edwards, 2003) and an overall better experience for the user. By providing this improved experience for the user, based on the insights of the interviews with the physiotherapists, the user is expected to be more inclined to use the product.

The development of the material selection model is a guide for future designers of DIHP and other customizable human-centred products. Understanding the steps to take in the material selection process can save time and resources in selecting the materials. Furthermore, having a systematic approach to material selection ensures no shortcuts are taken in the selection process, which avoids oversimplifying the selection process. And leads to an overall better material selection.

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However, it is important to mention that although the human-centred research pointed out some weak points for ABS+, the interviews with the material science experts showed that its issues could be addressed, such as post-processing or coating the problems. Other challenges the material science experts pointed out were regarding expected hygienic problems caused by air pockets in the products caused by the 3D printing process. Lastly, the experts questioned the implementation of the sensors in the product with the current 3D printing techniques. Therefore, a revision of the 3D printing process can be considered. A promising technique that could potentially solve these problems would be volumetric 3D printing, which would be able to print around the sensors(Stevenson, 2020). However, our model does not yet offer suggestions in such a direction but focuses more on material comparison and selection instead.

Additionally, only three materials were analysed due to the limited availability of resources and time. We expect that if more material alternatives were provided, the average ratings of the materials would be different. Furthermore, in our case study, only nine people participated in the feeling part, which may not be a representative sample size. Also, a wider variety of groups could be used, for instance, people from the target group, which would give valuable insights. Lastly, only one iteration of the material selection model has been included in this case study. Therefore, the full iterative potential of the material selection model is not tested in this study.

6 CONCLUSION AND FUTURE WORK

In this paper, we explained the novel material selection method for the material selection of DIHP. To achieve this, a material selection model has been made, which prescribes an initial property-based selection of materials, after which a feel team tests materials. In our work, we were inspired by Gr!pp, which is a kitchen utensil grip designed for stroke rehabilitation. Our model was tested by analysing the material selection of the Gr!pp, as a case study. From a database, 12 possible 3D printable materials were identified, of which ten were deemed feasible for the final research. From the ten possible materials, three have been tested by human-centred feel teams. Our material selection model is currently focused on customized DIHP. Therefore, further research should be conducted on the applications of this material selection model for other human-centred consumer products to understand the overall usability of the model.

Another point that could be further investigated would be the concrete steps to be taken in post-processing the prototypes after human-centred testing. In addition, how to concretely improve the products using coating and combining materials would give valuable insights into the different possibilities of improving the human-centred experience of the materials. Lastly, property-based requirements in their operational environment need further testing before testing the human-centred aspects.

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