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Nanosilica Particulate Magnetic as Alternative Filler on Natural Rubber Composites with Human-Tissue-Like Mechanical Characteristic

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ABSTRACT

There have been no reports of the simultaneous application of natural fillers, such as magnetite and natural zeolites, to increase the strength of composites containing silica (SiO2) fillers as reinforcing fillers in natural rubber. This study has investigated the effect of magnetically modified natural zeolite on nanosilica-reinforced natural rubber composites that include a mechanical characteristic like human tissue. We use technical specifications rubber (TSR) SIR 20 with nanosilica reinforced fillers and Titanate coupling agent (TCA) as fillers and elastomer binders. The results showed that the nanosilica-zeolite-magnetite (Fe3O4) mixture had an influence on strength and stiffness and could be a substitute filler. The precursors made with some variations include the optimization of filler and the optimization volume fraction of nanosilica. Mechanical characteristics of different human body part tissue were compared to the control samples and have similar mechanical characteristics with internal human tissue characteristic. Based on these results, nanosilica fillers combine with magnetically modified zeolites and titanate coupling agents, potentially as an alternative filler to replace carbon black, and are applicable for synthetic muscle replacement cadavers with a customized formula.

1. INTRODUCTION

In the realm of medical training, cadavers have long been the standard for surgical education and research. Yet, the utilization of human remains presents notable challenges, including their finite durability, significant expense, limited availability, and ethical controversies. Medical students often encounter a diverse array of cadaveric specimens, each with varying age and health conditions, resulting in inconsistent training experiences (Kaku, 2012; Giordano et al., 2021). With advancements in medical pedagogy, the imperative for alternative, non-human teaching modalities has intensified, particularly to instill patient care protocols in trainees prior to direct patient interaction. The risks involved in allowing novices to practice procedures on live patients necessitate the adoption of interactive devices and systems, which enable the safe acquisition of critical skills without endangering patient welfare (Lowe, 2015; Hart & Breslin, 2022).

These innovative training apparatuses serve not only medical professionals and students in honing clinical competencies—including patient care, medical knowledge, and system-based practice—but also empower patients in learning self-examination techniques. There exists an acute need within the medical community for realistic simulation structures to practice surgical tasks such as incisions, excisions of lesions, venous access, and suturing. Current simulacra falls short in authentically emulating the physical and aesthetic qualities of human tissue, underscoring the demand for an artificial substitute that can faithfully replicate the intricacies of human anatomy.

This investigation seeks to replicate the properties of human cadavers with a synthetic material, addressing the pressing demand for durable and ethical alternatives in medical training. Clinicians and researchers have long recognized the utility of silicone-based phantoms in clinical simulations for device testing and procedure training (Wang et al., 2014; Yin et al., 2021). The development of fiber-reinforced elastomeric (FRE) composites has expanded their application scope, enabling innovations such as dynamic flywheels, adaptive underwater vehicles, pliable aircraft surfaces, and biomechanical devices that parallel the flexibility of human tissue (Ayers et al., 2008; Murniati et al., 2017; Amiri et al., 2022). These composites, more pliant than traditional materials, can be engineered to exhibit a broad spectrum of physical properties, such as varying degrees of stiffness and elasticity, essential for realistic tissue simulation.

The innovative aspect of this research lies in the use of natural rubber, a material intrinsic to Indonesia, blended with a unique filler—termed nanosilica particulate magnetic—comprising nanosilica, natural zeolite, and magnetite. This approach leverages local resources to produce a cadaver substitute that faithfully replicates human tissue mechanics. The study delves into formulating a composite that demonstrates the desired mechanical fidelity and response to incisions, akin to human flesh.

For the composite matrix, we have selected natural rubber and have narrowed down the potential fillers to kaolin, calcium carbonate, and nanosilica, each known to influence the mechanical characteristics of the base material. The intent of this research is to identify the optimal filler that will endow the natural rubber with a biomechanical profile that closely mirrors that of human tissue. Subsequent optimization will involve adjusting the volume fraction of the chosen filler to refine the material's properties further.

2. METHOD

Basically, this experiment is divided into several phases: sample synthesis, material characterization, data retrieval, and analysis. Molds with precise requirements, suitable material, size, and performance are required. The stainless steel mold that is being used measures 10 cm in length, 7 cm in width, and 3 cm in height. In addition to serving as a container, matter also acts as a heater to speed up the curing maturity.

Table 1 Materials Formula.

Optimization	Sample	Materials [Particle-to-Hole Ratio (phr)]								
		Rubber	***Oil***	**ZnO**	**Stearic Acid**	***filler***	**paraffin**	**CMC**	**TCA**	**Sulfur**
Filler type	Control	100	8	5	2	-	1	0.5	1	2.25
	Caolin	100	8	5	2	7.5	1	0.5	1	2.25
	$CaCO_3$	100	8	5	2	7.5	1	0.5	1	2.25
	Nanosilica	100	8	5	2	7.5	1	0.5	1	2.25
Volume fraction nanosilica particulate magnetic	0	100	8	5	2	0	1	0.5	1	2.25
	0.021	100	8	5	2	2.5	1	0.5	1	2.25
	0.041	100	8	5	2	5	1	0.5	1	2.25
	0.060	100	8	5	2	7.5	1	0.5	1	2.25
	0.078	100	8	5	2	10	1	0.5	1	2.25
	0.096	100	8	5	2	12.5	1	0.5	1	2.25

The precursor synthesis will be made of composite materials. Overall, this study is dependent on the first stage because the constituent materials affect the character of the material. Samples were synthesized by mixing several chemicals (Table 1), the formula that is used depends on the type of materials used, the order in which they are added, the amount of time the mixture is stirred, and the amount of material used. All formulas were tried out and repeated continuously until it was found to be the most appropriate to produce a nanocomposite most similar in structure mechanics to human flesh.

Mix the precursor for a predetermined amount of time with a foaming agent and a curing agent (according to the formula), and then add the stabilizer and gelling agents. Another sample, which contained filler, was combined with a stabilizer and gelling agent. The material and precursors are then dried and burned (Davis, 2004). Use a softener and activator to facilitate the composite's mixing process. After that, the composite was put into the oven for two hours at 150 °C and then inserted into the mold molding and curing hot press for 1 hour at 100 °C.

Optimization of the addition of filler material with a combination of volume fractions of nanosilica, zeolite and Fe_3O_4. The compounding procedure was carried out according to the American Society for Testing and Materials (ASTM)-D 3184-80. Composites were made using a two-roll mill. The manufacture of composites is carried out by the composite melting method using a mixture of Standard Indonesian Rubber (SIR) 20 natural rubber obtained from PT Perkebunan Nusantara VIII (Bandung, Indonesia). After determining the fundamental properties of the rubber material, particularly latex, research was conducted on filler variations such as kaolin, $CaCO_3$, and nanosilica. Other chemicals are used at the technical level.

The materials mentioned in the columns of Table 1 are processing aids for the manufacture of natural rubber composites with their respective functions. Before adding sulfur, 7.5 phr of filler mass was added to the composite; with this filler variation, the highest Young's modulus value was obtained for the nanosilica filler. Sulfur as a curing agent, triggers the crosslinking process to produce rubber goods that have high tensile strength and the addition of breaking while reducing the vulcanization process using an accelerator (MBT, mercaptobenzothiazole) and activator (ZnO, stearic acid). Stabilizers on polymers are used to prevent effects that can change the characteristics of the material, such as oxidation, recombination, and crosslinking caused by the oxidation of polymers. The quality of the stabilizer itself depends on the degree of solubility, its effect on the viscosity of the material, and its ability to stabilize the polymer matrix. Stabilizers in polymers are used to prevent effects that can change the characteristics of the material, such as oxidation, recombination, and cross-linking caused by polymer oxidation. The quality of the stabilizer itself depends on the degree of solubility, its effect on the viscosity of the material, and its ability to stabilize the polymer matrix. The stabilizer used in this experiment is paraffin wax which can also be said to be an anti-oxidant, anti-ozone to produce rubber products that are resistant to aging, and adjustment of the vulcanization system. Methods to strengthen physical properties and reduce processing costs by increasing the volume can be added with fillers, while to facilitate processing so that good mixing occurs, oil processing is used. Titanate coupling agent (TCA) is used for good filler dispersion, good compound flow, and good crosslinking connectors.

The gelling agent is a material that functions to increase the viscosity of a liquid or material without changing the characteristics of the material. The gelling agent thickens the material and forms it into a gel. Before adding the gelling agent to the composite, three fillers with a combined mass of 6 grams were added: Caolin, $CaCO_3$, and Silica Nanoparticles. Gelling agents dissolve in liquids as colloidal mixtures that form an internal cohesive structure. In this experiment, CMC (carboxymethyl cellulose) was used as a gelling agent. CMC itself is a carboxymethyl (-CH2-COOH) chain bound to hydroxyl chains from glucopyranose monomers, which are the backbone of cellulose. In this experiment, it was used in the form of its sodium salt or sodium carboxymethyl cellulose. Mechanical tests were run using Universal Testing Machine. For this mechanical test, the material must be in a solid state.

3. RESULTS AND DISCUSSION

3.1 Filler Variations

The goal of filler optimization is to select the optimal filler for the production of synthetic muscle using liquid latex as a base material. After determining the fundamental properties of the rubber material, particularly latex, research were conducted on filler variations such as Caolin, $CaCO_3$, and nanosilica. As a control, the composite samples without filler are depicted in Figure 1.

(a) (b) (c) (d)

Figure 1 Samples of synthetic muscle with various fillers: (a) no filler, (b) Caolin, (c) $CaCO_3$, and (d) nanosilica.

The highest Young's modulus value was obtained for the nanosilica filler, with 7.5 phr of filler mass variation. This outcome serves as a filler reference for future optimization. It has been well understood that a small amount of filler particles can significantly alter an elastomer's mechanical response. In particular, it is known that the addition of filler particles can: (1) increase the stiffness of the material; (2) change the strain history dependence of the stiffness (commonly referred to as the Mullins effect); (3) alter time-dependent aspects of material behavior, such as hysteresis and stress relaxation.

Although it is well known that filler particles can change these crucial features of elastomeric materials' macroscopic stress-strain behavior, the exact process by which the changes take place is still up for debate For instance, the increase in stiffness is thought to be caused by two main factors: (i) the continuum level explanation, according to which the stiffness of a composite will be some weighted combination of the stiffnesses of the individual constituent materials, depending on the precise microstructure; and (ii) the molecular level explanation, according to which the filler acts to both effectively increase the crosslink density of the material by providing additional crosslinking sites at the molecular level. The size, type, and shape of the fillers; the structure of the filler aggregate; and the area of the polymer-filler interface are a few state factors that have been postulated to affect the magnitude of these contributions, in addition to the volume fraction of filler particles.

The sample was then tested to see the mechanical characterization of various types of filler. Figure 2 shows the composite hardness value to be between 45 and 50 shore A, which is still in the optimal range for rubber composites (40-60 shore A). The crosslink density value is linear with composite Young's modulus value. The best result of mechanical characterization is nanosilica filler for 7.5 phr.

In practice, mechanical tests must additionally examine viscoelastic qualities in addition to stress-strain tests. A stress-strain curve represents the results of this test's data collection. We can calculate the Young's modulus of composites. The sample test results can be obtained by curve force versus length change, the area elastic force curve of the change in length (dF) along the slope (dl) is then used to calculate Young's modulus. The curve of force to length shows there is a significant difference in the third characterization sample.

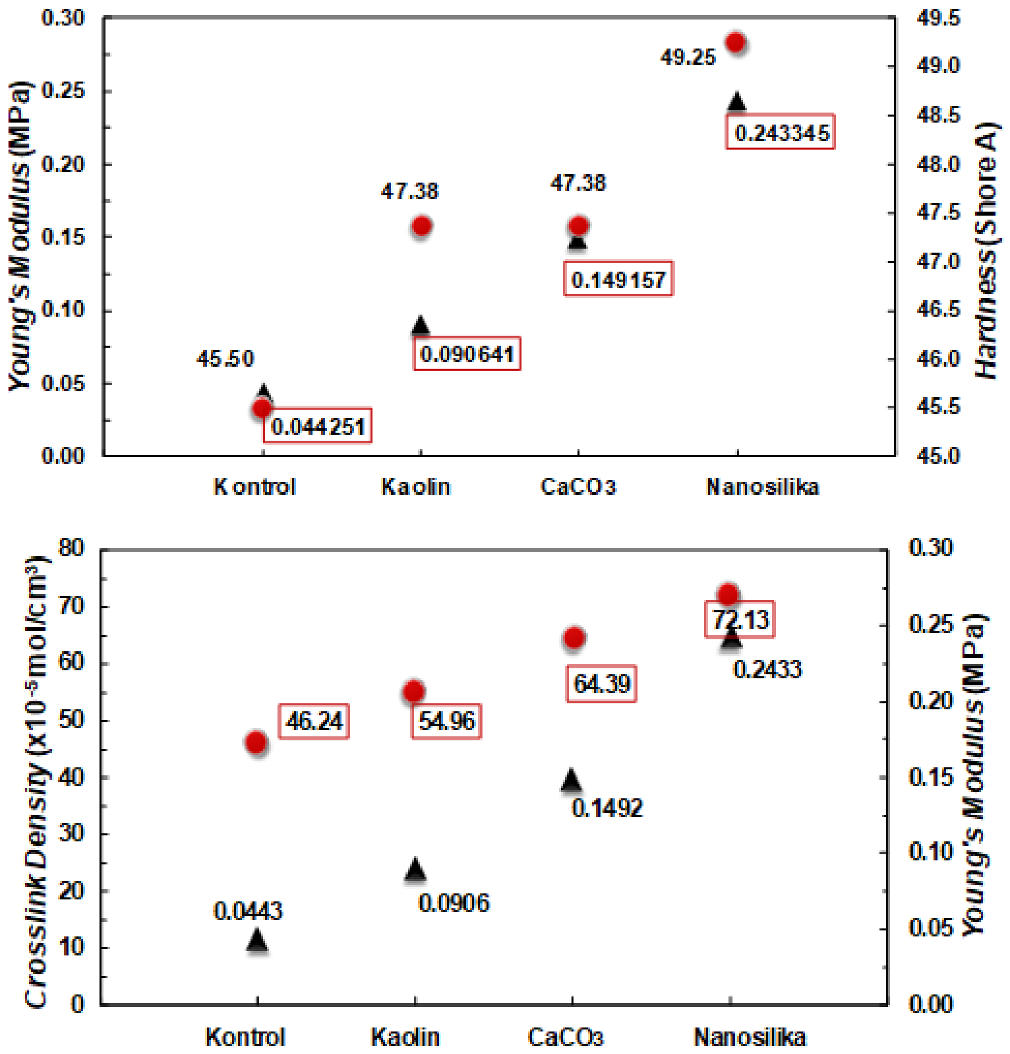

Figure 2 Results of mechanical characterization: Young's modulus (top) and crosslink density (bottom), of various types of filler with a sample mass of 9 g (7.5 phr) with curing 150° for 2 hours.

The highest Young's modulus results are the sample with nanosilica filler. This outcome serves as a filler reference for next optimization, nanosilica volume fraction variations. Young's modulus linear with polymer's strength because reversible elastic behavior frequently displays a linear relationship between stress and strain. The orientation of the polymer chains is random in a thermoplastic polymer tensile sample. A neck forms when stress is applied because of the local alignment of the chains. The neck keeps expanding up to the alignment of the chains along the entire gage length. The polymer's strength is then increased.

3.2 Nanosilica Volume Fraction Variations

Nanosilica shows more constant experimental results and better material strength than other fillers (Table 2). So that by using nanosilica filler it will be easier to manipulate the characteristics. Figure 3 shows a synthetic muscle sample with a volume fraction variation of nanosilica from 0-12.5 phr, resulting in a composite with mechanical characteristics as shown in Figure 4.

Table 2 Result data of filler variation.

Sample	Surface area (mm^2)	*dF*/*dl*	Modulus Young (MPa)
Control 1	13000	5.7526	0.044251
Control 2	13000	15.267	0.117438
Control 3	16000	8.6563	0.054102
Caolin 1	19000	4.013	0.021121
Caolin 2	17000	4.0165	0.023626
Caolin 3	17000	15.409	0.090641
$CaCO_3$ 1	14000	5.4694	0.039067
$CaCO_3$ 2	14000	20.882	0.149157
$CaCO_3$ 3	16000	21.86	0.136625
NS 1	13000	26.87	0.206692
NS 2	11000	26.768	0.243345
NS 3	9000	18.002	0.200022

The highest Young's modulus value is found at a volume fraction of 0.08 nanosilica (10 phr) and the crosslink density value is linear with the Young's modulus value of the composite (Figure 4). It can be said that the excess amount of filler at a certain value will reduce the value of Young's modulus and crosslink density. The high and low value of Young's modulus of a material can be used to describe the mechanical characteristics of the material. One material that can have its mechanical properties measured and observed in human tissue. The following information is collected from sources that discuss the mechanical properties of the human body. The data will then be compared with the literature on the mechanical characteristics of the human body (Murniati, 2018; Yamada et al., 2022). If the experimental findings are compared with the characteristics of the human body using Young's modulus data, it can be said that the Calcium Carbonate rubber composite of test 1 has mechanical properties (0.039 MPa) similar to the mechanical properties of the human gut (0.0356 MPa) (Edwards et al., 2005; Hartrumpf et al., 2022). Nanosilica rubber composites of test 2 (0.149 MPa) and test 3 (0.136 MPa), as well as calcium carbonate rubber composites, have properties similar to knee cartilage in young adults (0.13MPa) (Egorov et al., 2002; Chansoria et al., 2022). Whereas the 6 g nanosilica rubber composite (0.086 MPa) in test 2 resembled the human esophagus (0.077 MPa) in some respects (Wren et al., 2001; Guo et al., 2022).

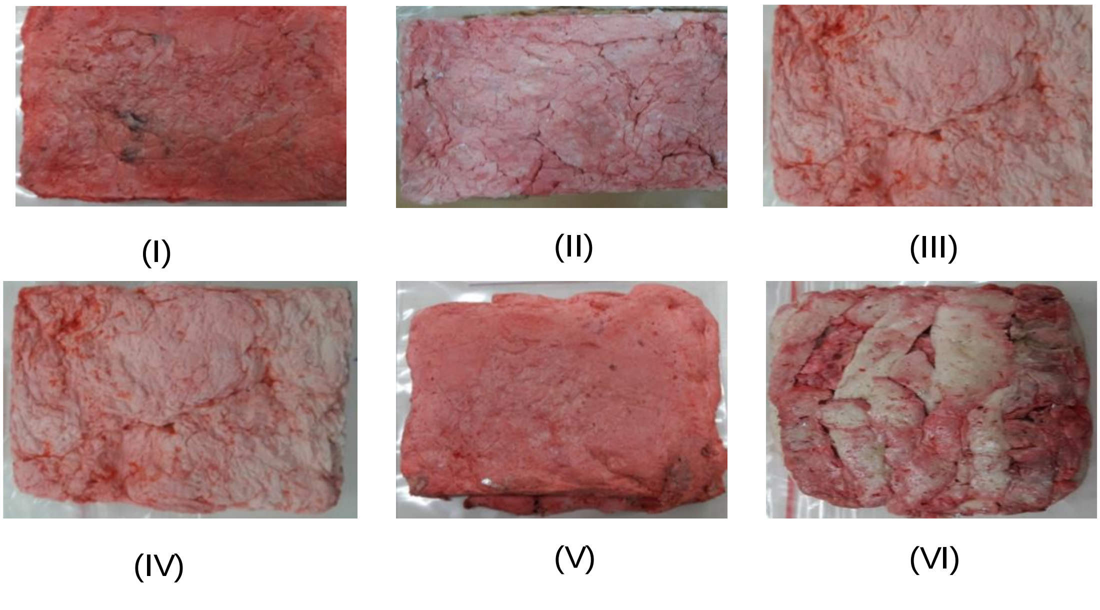

Figure 3 Synthetic muscle samples of nanosilica volume fraction variation.

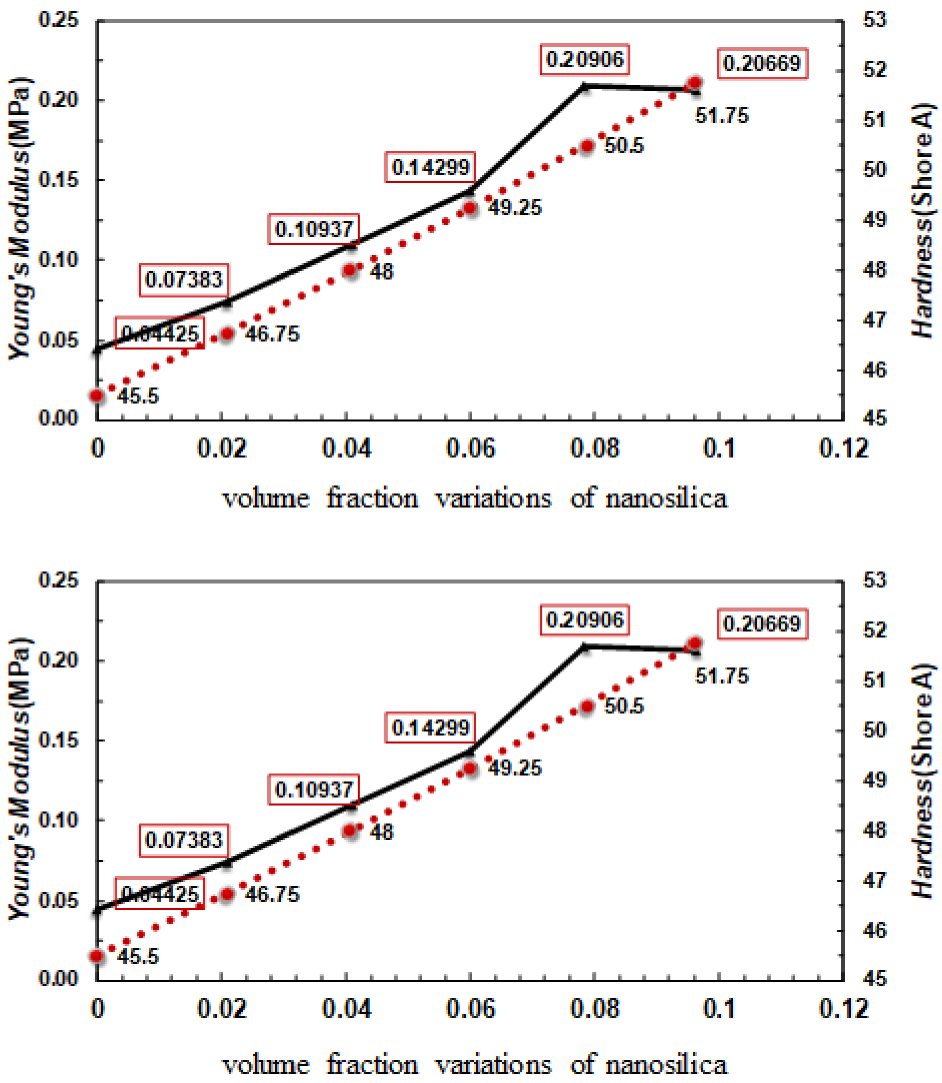

Figure 4 Results of mechanical characterization: Young's modulus (top) and crosslink density (bottom), of volume fraction variations of nanosilica with curing at 150° for 2 hours.

4. CONCLUSION

This study examined the appropriateness of kaolin, calcium carbonate, and nanosilica as fillers in natural rubber composites to mimic human muscle tissue. Results showed that the mechanical characteristics of composites consisting of calcium carbonate and kaolin did not significantly differ from those of the control rubber in visual appearance, hardness, and density measurements. The addition of nanosilica led to a composite material that featured a significantly increased Young's modulus and higher density, bringing it closer in mechanical properties to that of natural muscle. Notably, the synthetic muscle with a 10 phr nanosilica filler possessed a Young's modulus (0.209 MPa) almost identical to that of beef muscle (0.21 MPa), indicating the potential usefulness of this composite material in medical simulations.

Furthermore, the addition of amorphous silica as a filler into the Standard Indonesian Rubber (SIR) 20's natural rubber technical specifications rubber (TSR) compound increased the crosslink density, morphological, and mechanical properties. The objective insights from this study elucidate how diverse additives affect the physical properties of rubber compounds. Our study emphasizes the positive influence of zeolite on the reinforcement of nanosilica-based composites. Such an impact is facilitated by a Titanate coupling agent, which effectively strengthens the bond between the filler and elastomer.

Not only do these findings achieve the objective of identifying a suitable filler to approximate the mechanical characteristics of human muscle, but they also pave the way for refining the composite's properties to enhance realism in medical training applications. Future investigations could build on this work by examining the longevity and biocompatibility of these materials in clinical settings.

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