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PRINCIPAL INVESTIGATOR: Sang-Eun Song

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6. AUTHOR(S)
Sang-Eun Song (PI) and Hyoung Jin Cho (co-I)

E-Mail: sam0song@gmail.com, hjcho@ucf.edu

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12201 Research Parkway
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14. ABSTRACT

The goal of the project in Year 1 is to design and fabricate prototype of the proposed bone harvesting device and micro saw that enable root-side cutting of donor for osteochondral autograft transplantation. We designed the proposed bone harvesting device with tension mechanism as well as open ends oscillating mechanism as an alternative solution. Also, a flexible micro saw with timing-belt like drive mechanism was designed to overcome limitations of complexity and cutting strength. An animal bone cutting test demonstrated that the fabricated micro saw with oscillating cutting is capable of cutting the bone, which has been published as a journal paper. The study will be presented at the 2023 Military Health System Research Symposium (MHSRS).

15. SUBJECT TERMS
Micro saw; surgery; microfabrication; electroplating; osteoarthritis; osteochondral autograft, transplantation (OAT)

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1. Introduction

The proposed project is to develop a new robotic orthopedic surgery procedure employing a novel micro saw mechanism that can extract a preoperatively planned bone-cartilage donor for autologous transplantation to treat severe osteoarthritis. Osteochondral autograft transplantation (OAT) has been performed to repair such cartilage defects. Plugs of healthy cartilage with subchondral bone are extracted from non-load bearing area and inserted into the arthritic defect. Widely performed Mosaicplasty extracts and transplants multiple small cylindrical grafts as an alternative to a full surface transplantation since no method exists to extract larger or non-cylindrical donor graft intact as it requires cutting the root-side of donor. To overcome the fundamental limitation of donor root-side access, a novel osteochondral tissue extraction method has been designed using a new transversal blade micro saw. The ultimate goal of the proposed research is to enhance surgical outcome of OAT by providing a robotic procedure that can extract and transplant a custom-shape single piece autograft donor using a micro chainsaw. The central hypothesis is that if defect-specific personalized-shape autograft can be extracted safely and placed into a precisely prepared defect area, more successful intact single donor transplantation can be achieved instead of utilizing multiple small plugs. In this proof-of-concept project, our approach to test the hypothesis is to prototype the root-side bone cutting device integrated to a standard robotic arm and perform mockup OAT procedures using foam and animal bones. In this technical discovery project, we focus on prototyping and testing the feasibility of the root-side bone cutting mechanism using a transversal blade micro saw.

2. Keywords

Micro saw; surgery; microfabrication; electroplating; osteoarthritis; osteochondral autograft, transplantation (OAT)

3. Accomplishments

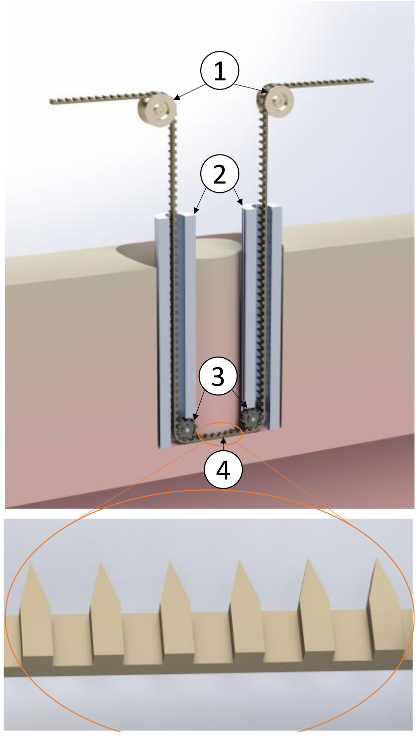

Figure 1. CAD model of donor root-side cutting mechanism showing (1) micro chainsaw guides inserted in donor profile (drilled), (2) pulley, (3) saw driver, and (4) micro saw (bottom) zoomed view of micro saw in action.

The main goals of the project in Year 1 are design and prototype of the proposed bone harvesting device and micro saw. As the design of the bone harvesting device is based on the micro saw design and its operation mechanism, we focused on the design and prototype fabrication of the micro saw. In addition, we also investigated alternative mechanisms for saw operation.

In project year 1, design and fabrication of the proposed robotic surgery system was focused especially the fabrication and operation feasibility of the micro scale saw. Accordingly, overall design and operational mechanism of the surgical robot was developed with some minor modifications such as adopting open loop oscillation rather than continuous circulation of micro saw. For the micro saw, in particular, we found that the proposed chainsaw design is technically highly challenging because of high-speed operation of assembled micro chainsaw joint structures, which may cause early material fatigue thus failure. To minimize the problem, we designed, prototyped, and tested a flexible micro saw that can be bent in small radius without chain structures (Fig. 1). The bone-cutting strength tests of the micro saw demonstrated that the micro saw fabricated by metal plating exceeds the bone cutting strength. We produced a preliminary design and fabrication of a novel micro saw mechanism utilizing transversal blades that can extract a preoperatively planned bone-cartilage donor for autologous transplantation to treat severe osteoarthritis.

Micro saw fabrication using electroplating: Electroplating can be employed as one of the micromachining technologies when combined together with photolithography to make miniaturized devices with various types of metals such as nickel, gold, silver, copper, and their alloys. Electrical, mechanical, and magnetic characteristics, as well as chemical homogeneity of the metal layer, are the main parameters to control for a high-performance component. Therefore, it is critical to control, optimize, and standardize the fabrication parameters. In order to fabricate the micro saw with transversal blades, resembling a miniature timing belt with sideway blades, an electroplating process combined with two-step photolithography was used (Fig. 2). The micro saw was designed with a simple structure

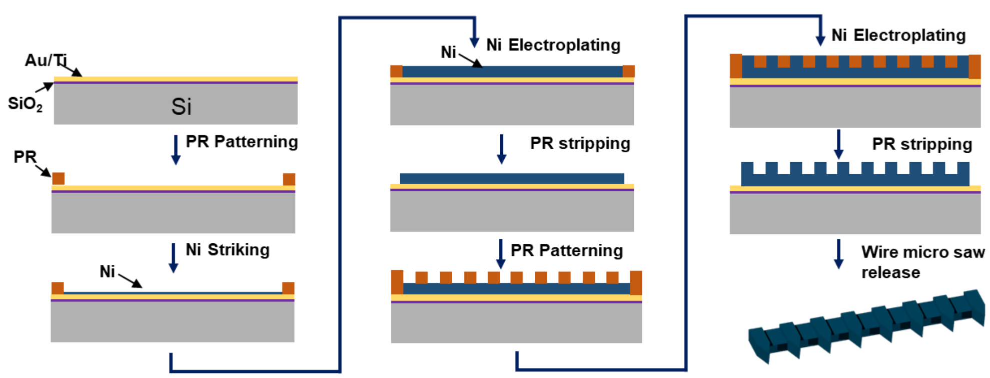

Figure 2. Schematic illustration of micro saw fabrication process.

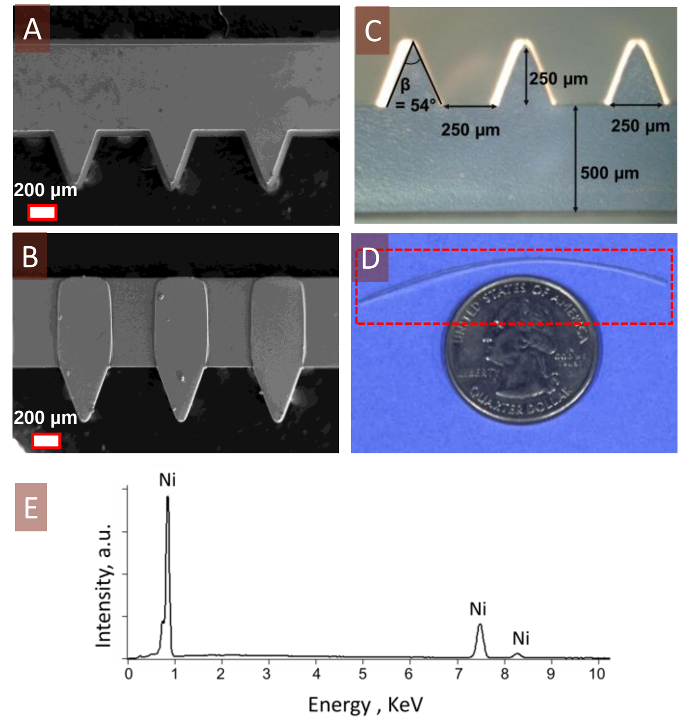

Figure 3. (A, B) SEM images of the fabricated micro saw bottom, and top view, (C) 3D optical microscope image showing micro saw tooth anatomy, β = wedge angle, (D) photograph of the fabricated micro saw size comparison with the US quarter coin, and (E) EDX analysis of the device.

without a mechanical connector to maximize its lifetime. Multiple micro saw segments were fabricated using a 3-inch oxidized silicon wafer. First, Au/Ti thin film was deposited using e-beam deposition. Then, the AZ 40XT photoresist was spin-coated at 800 rpm for 30 sec and baked at 75℃ for 120 s, at 105℃ for 120 s, and at 125℃ for 180 s. Later, the substrate was exposed to UV using an EVG aligner and developed using AZ300MIF to create the patterns. The nickel seed layer was electro-deposited on the exposed area using a 10mA/cm^2 current density for 10 min. The nickel seed layer acts as a nucleation layer and provides the conducting path for electroplating. Nickel plating was done using a commercially available nickel sulfamate electroplating solution. The plating process was conducted by using a pulse current of 10mA/cm^2 with a duty cycle of 0.5 at 55℃. In this process, the photoresist pattern was used to create the metallic structure, and later it was removed using acetone. After fabricating the bottom layer, a similar process was used to fabricate the top layer for micro saw driver teeth. Finally, micro saw segments were separated from the silicon substrate by etching underneath Au/Ti layer. The thickness of the fabricated nickel micro saw is 200 microns, which makes it flexible, allowing the micro saw to bend along the cut with the desired degree of curvature. We have also designed and fabricated micro saw drivers to engage the micro saw during its operation using the same fabrication steps as the blades (Fig. 3).

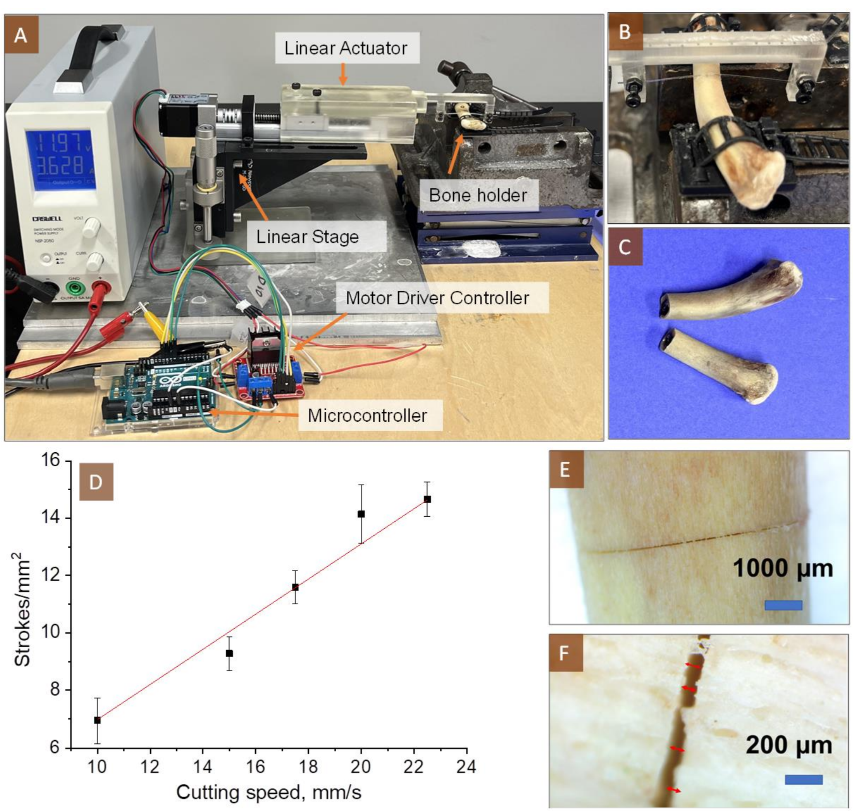

Figure 4. (A) Bone cutting setup, (B) a zoomed view of micro saw in action, (C) a picture of the bone showing uniform cutting, (D) number of strokes per unit area vs. cutting speed, and (E, F) optical microscope images of a bone cut at different magnification showing the uniform sub-100-micron wide cut.

Prototype evaluation: A novel nickel micro saw prototype is fabricated using the photolithography technique in combination with electroplating to be able to extract a personalized autograft from a donor site for osteochondral autologous transplantation. The fabricated micro saw has the saw teeth aligned perpendicular to the direction of the micro gear teeth to cut the root-side of the doner. In addition, the thickness of the micro saw ~200 µm with 750 µm in width was achieved suitable for operating within a small drilling path, less than 2 mm. The fabricated parts were visually inspected by 3D optical microscopy, showing the successful fabrication of the micro saw and the micro saw driver. Micro indentation was performed to derive mechanical properties for evaluating the integrity of the fabricated micro saw. The elastic modulus and hardness values of the micro saw are 209 ± 2.04 GPa and 6.39 ± 0.0940 GPa, respectively, which are about an order of magnitude higher than those exhibited by human bones. To demonstrate the cutting capacity of the micro saw, we designed a micro saw holder using a 3D printer and demonstrated the cutting of chicken bones (Fig. 4).

Opportunities for training and professional development: Nothing to Report.

Results disseminated to communities of interest: Nothing to Report.

Plan for the next reporting period to accomplish the goals: next goals are to fabricate a full-length micro saw prototype and its driver components that will be assembled as the bine harvesting device. The device will be then attached to a standard robot for mockup procedure testing.

4. Impact

The novel micro saw with integrated micro saw driver teeth was successfully fabricated, which is a unique micro-scale mechanism that has not been utilized for clinical purposes. The flexibility and bone-cutting capacity of the micro saw demonstrated its potential for numerous small-scale precision and/or minimally invasive cutting tasks in medicine. The main challenge in the proposed approach is that the micro saw needs to travel through a pair of guide tubes along the donor profile cut (2mm or less). Our micro saw and driver design and prototyping achieved a micro saw with integrated driver teeth having 750 µm in width with 200 µm thickness which is small enough to meet such a requirement. The success of the mechanism could potentially transform current cartilage-bone transplantation procedures. Further, a sub-millimeter wire-like flexible saw can be a powerful tool to overcome limitations of current medical tools potentially enabling new procedures that have not been possible up to date.

5. Changes/Problems

Micro chain saw segments were fabricated to test its feasibility. However, such joints in micro scale seemed not suitable for high-speed actuation. As an alternative, we designed a flexible timing-blet like micro saw without friction inducing joints. We will still prototype the micro chain saw prototype to perform comparative tests to quantify performance differences.

An oscillating saw driver mechanism also has been designed as an alternative to the continuous rotational feed. These two mechanisms have advantages and disadvantages in terms of robotic operation and bone cutting performance. Oscillating drive, however, has the key advantage of less directional reaction force which can be critical for the operational stability of the robotic device.

Having teeth-like cutting edges are common for various cuttings. However, fabrication of such especially in micro scale is highly challenging for fabrication and cutting strength. As an alternative, we have been investigating other electroplating methods.

6. Products

Journal publication:

P. Pathak, J. Fasano, Y-C. Kim, S-E. Song, H.J. Cho. Design and Fabrication of Micro Saw Enabling Root-Side Cutting of Bone. Micromachines 2023, 14, 856. https://doi.org/10.3390/mi14040856 (published, this grant acknowledged)

Abstract and Poster Presentation:

P. Pathak, J. Fasano, Y-C. Kim, S-E. Song, H.J. Cho. “Design and Fabrication of Micro Saw for an Osteochondral Autograft Transplantation,” Poster will be presented at 2023 Military Health System Research Symposium (MHSRS); 2023 August; Kissimmee, FL. (abstract accepted, poster will be presented, this grant acknowledged)

Invention Disclosure for Provisional Patent:

H.J. Cho, S-E. Song, P. Pathak. “Design and fabrication method of a micro saw with a timing belt like drive mechanism capable of providing transversal cutting of bone like material,” (in institutional review, this grant acknowledged as the main support)

7. Participants & Other Collaborating Organizations

Name:	Sang-Eun Song
Project Role:	PI
Researcher Identifier (e.g., ORCID ID):	https://orcid.org/0000-0001-8579-2008
Nearest person month worked:	1.5
Contribution to Project:	Dr. Song provides expertise on mechanism and design of the proposed device and micro saw.
Funding Support:	Nothing to Report

Name:	Hyoung Jin Cho
Project Role:	Co-I

Researcher Identifier (e.g., ORCID ID):	NA
Nearest person month worked:	0.5
Contribution to Project:	Dr. Cho provides expertise on micro fabrication and electroplating for micro saw development.
Funding Support:	Nothing to Report

Name:	Ramsey Kinney
Project Role:	Co-I
Researcher Identifier (e.g., ORCID ID):	NA
Nearest person month worked:	0.4
Contribution to Project:	Dr. Kinney is an orthopedic surgeon providing feedback and advice on the intervention design and operation.
Funding Support:	Nothing to Report

Name:	Pawan Pathak
Project Role:	Research fellow
Researcher Identifier (e.g., ORCID ID):	NA
Nearest person month worked:	0.4
Contribution to Project:	Dr. Pathak provides expertise on the micro saw design and electroplating fabrication.
Funding Support:	Nothing to Report

Name:	Pradipta Biswas
Project Role:	Graduate Student
Researcher Identifier (e.g., ORCID ID):	NA
Nearest person month worked:	1
Contribution to Project:	Mr. Biswas worked on the bone harvest device design and operational mechanism development.
Funding Support:	Nothing to Report

Name:	Jack Fasano
Project Role:	Undergraduate Student
Researcher Identifier (e.g., ORCID ID):	NA

Nearest person month worked:	3
Contribution to Project:	Mr. Fasano provides computer aided design, development, and operation of the bone cutting test rig.
Funding Support:	Nothing to Report

Other Collaborating Organizations: Nothing to Report.

8. Special Reporting Requirements

Nothing to Report.

9. Appendices

A1. Journal paper published:

P. Pathak, J. Fasano, Y-C. Kim, S-E. Song, H.J. Cho. Design and Fabrication of Micro Saw Enabling Root-Side Cutting of Bone. Micromachines 2023, 14, 856. https://doi.org/10.3390/mi14040856

A2. Abstract/Poster accepted:

P. Pathak, J. Fasano, Y-C. Kim, S-E. Song, H.J. Cho. "Design and Fabrication of Micro Saw for an Osteochondral Autograft Transplantation," Poster will be presented at 2023 Military Health System Research Symposium (MHSRS); 2023 August; Kissimmee, FL. *Accepted*

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Communication

Design and Fabrication of Micro Saw Enabling Root-Side Cutting of Bone

Pawan Pathak [1], Jack Fasano [1], Young-Cheon Kim [2], Sang-Eun Song [1,*] and Hyoung Jin Cho [1,*]

[1] Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, FL 32816, USA; pawan.pathak@ucf.edu (P.P.)
[2] Research Center for Energy and Clean Technology, School of Materials Science and Engineering, Andong National University, Andong 36729, Republic of Korea
* Correspondence: s.song@ucf.edu (S.-E.S.); hjcho@ucf.edu (H.J.C.); Tel.: +1-407-823-5014 (H.J.C.)

Abstract: A novel micro saw was fabricated using a combination of photolithography and electroplating techniques, resembling a miniature timing belt with sideways blades. The rotation or oscillation direction of the micro saw is designed to be perpendicular to the cutting direction so that transverse cutting of the bone is attainable to extract a preoperatively planned bone-cartilage donor for osteochondral auto-graft transplantation. The mechanical property of the fabricated micro saw obtained using the nanoindentation test shows that the mechanical properties of the micro saw are almost an order of magnitude higher than bone, which indicates its potential bone-cutting application. To demonstrate the cutting capability of the fabricated micro saw, an in vitro animal bone cutting was performed using a custom test rig consisting of a microcontroller, 3D printer, and other readily available parts.

Keywords: micro saw; surgery; microfabrication; electroplating; osteoarthritis; osteochondral auto-graft transplantation (OAT)

Citation: Pathak, P.; Fasano, J.; Kim, Y.-C.; Song, S.-E.; Cho, H.J. Design and Fabrication of Micro Saw Enabling Root-Side Cutting of Bone. *Micromachines* **2023**, *14*, 856. https://doi.org/10.3390/mi14040856

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1. Introduction

Osteoarthritis (OA) is one of the most common joint disorders with symptoms such as pain, inflammation, decrease in the range of motion, and reduction in activities of daily living [1]. Globally, OA affects nearly 528 million population, which is estimated to increase due to an increase in the aging population and obesity [2]. The study has shown that the causes of OA are being overweight, repetitive joint movements, aging, history of injury, low bone density, and muscle weakness, and it is a leading cause of disability in activities of daily living [3]. OA can occur in any joint in the body; it is most common in repetitive load-bearing joints because the flexible tissue (cartilage) at the end of the bone wears down, and the bone begins to change. Since the cartilage does not have blood vessels, nerves, or lymph, the healing of OA has been proven to be challenging [4]. Thus, treatment often requires surgical intervention. The typical treatment procedure involves removing the defect area and transferring the patient's own bone and cartilage (osteochondral grafts) from the low load-bearing area, known as osteochondral auto-graft transplantation (OAT) [5]. Since this procedure uses the patient's own tissue, it eliminates the risk of infectious disease transmission and helps treat smaller osteochondritis dissecans lesions [6]. In addition, the defective bone can be filled with mature hyaline cartilage; thus, the cartilage and bone can be treated simultaneously [7].

Mosaicplasty is a well-known technique since small cylindrical autografts can easily be extracted and then can fill any defect shape. Multiple grafts are able to resurface 80–100% of the damaged area [8], but studies have shown that having a gap between cartilages can result in poor histologic properties of the cartilage [9]. The current tool for removing the donor graft in OAT surgery is a manually inserted hollow cylindrical rod that is used to break the base of the donor graft [10,11], as shown in Figure 1. After removing the donor graft, its base is cut to implant into the defect site [12]. The technological limitation of this procedure is precisely filling the prepared defect area with multiple healthy osteochondral donor grafts. To overcome this limitation, a bone-cutting mechanism that can harvest a predetermined shape and length of the donor graft is required. The working mechanism of the proposed OAT surgery technique is described in detail in the previous work [13,14]. K-wires or cylindrical hollow drill bits can be used to make the cylindrical cut of the donor graft [15]. For the transverse cutting of the donor graft, a unique micro saw is required, which is not currently available, and this work is focused on fabricating a micro saw for this application. The minimum requirements of the micro saw for this application are the width of the micro saw to be less than 1 mm and the micro saw capable of in situ transverse cutting of donor graft. We hypothesize that such a micro saw can be fabricated using micro electroplating and photolithography, and the fabricated micro saw will be strong enough to cut the bone. The advantages of the proposed technique are a decrease in bone stress (donor site), precise cut, and optimal use of the donor graft.

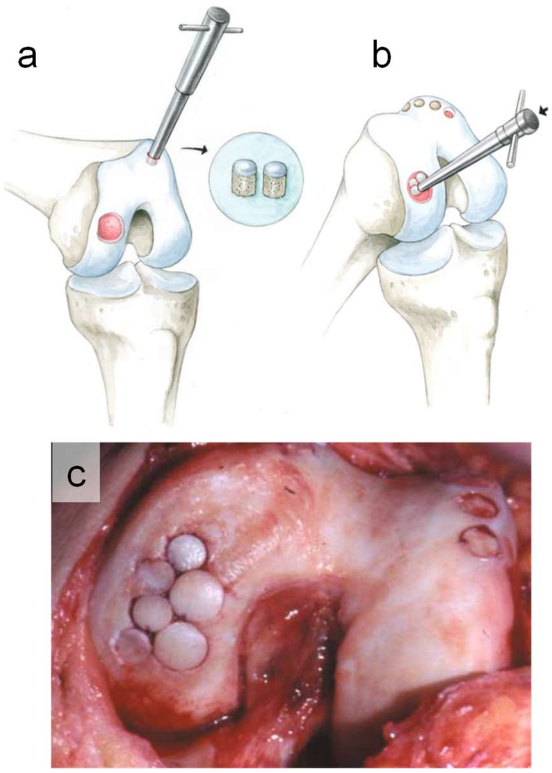

Figure 1. Illustration of OAT surgery technique showing (**a**) defect debridement and donor graft harvesting, (**b**) implantation of the donor grafts into the defect, and (**c**) picture of the bone showing donor grafts implantation into the defect. The figure is reproduced from ref. [16].

Advancements in engineering have made available numerous micromachining technologies that have been utilized in fabricating medical devices [17–19]. Electroplating can be employed as one of the micromachining technologies when combined with photolithography to make miniaturized devices with various types of metals such as nickel, gold, silver, copper, and their alloys [20,21]. Electrical, mechanical, and magnetic characteristics, as well as chemical homogeneity of the metal layer, are the main parameters to control for a high-performance component [22,23]. Therefore, it is critical to control, optimize, and standardize the fabrication parameters. Electroplating with the modulated DC (direct current) at a specified duty cycle, known as pulse electroplating, is popular for micro electroplating [24]. In pulse electroplating, elimination of the hydrogen embrittlement due to the depletion of cation species in the pulsating diffusion layer improves homogeneity, decreases porosity, and enhances adhesive strength [25,26]. The enhancement of the mechanical characteristics of nickel was also observed when the size of the electroplated nickel structure was reduced [27]. This favorable scaling effect, biocompatible nature, and its native mechanical properties make the electroplated nickel a superb candidate for the micro saw blade.

This research aims to develop a micro saw using a biocompatible material that is capable of precisely removing the defected area and root-side cutting of the donor graft. In order to achieve these goals, the nickel micro saw with transversal blades was designed and fabricated, resembling a miniature timing belt with sideways blades using an electroplating process combined with two-step photolithography. The micro saw was designed with a simple structure without a mechanical connector to maximize its lifetime. The mechanical, morphological, and chemical properties of the fabricated micro saw were studied in detail.

2. Materials and Methods

2.1. Chemicals

Acetone, isopropanol, nickel chloride, and methanol were obtained from Sigma-Aldrich (St. Louis, MO, USA). AZ 40XT photoresist and MIF 300 developer were obtained from Microchemicals GmbH (Nicolaus-Otto-Straße, Ulm, Germany). Nickel sulfamate electroplating bath solution was purchased from Technic Inc., Cranston, RI, USA. All these chemicals were used without additional purification.

2.2. Design of Micro Saw

The schematic illustration of the design of the micro saw and its working mechanism is presented in Figure 2. In order for precise custom defect removal and autograft donor harvesting, a novel micro saw design is required, which is currently unavailable. Figure 2 illustrates the micro saw operation mechanism in which the saw operates through guide tubes. The micro saw guide will ensure that the micro saw will not damage the bone wall during its operation. The two main requirements for such an operation are: (a) the micro saw is small enough to travel inside the saw guide at ~1 mm diameter; and (b) the micro saw blades are perpendicular to the travel loop. This work mainly deals with designing and fabricating the prototype micro saw that meets the above requirements. The micro saw was designed in such a way that it has blades perpendicular to the direction of the motion, which has the advantage of root-side cutting of the bone. The micro saw will resemble the micro timing belt, with the blade perpendicular to the gear teeth. It was also designed to be single-use to prevent the risk of cross-contamination and infection. The fabricated prototype includes the micro saw, and the micro saw driver.

2.3. Fabrication of Micro Saw

The micro saw with transversal blades was fabricated by photolithography in combination with electroplating. Multiple micro saws were fabricated using a 3-inch oxidized silicon wafer. Figure 3 shows the schematic illustration of the fabrication process. First, 10 nm of Ti and 100 nm of Au thin film were deposited using an e-beam deposition. Then, the AZ 40XT photoresist was spin-coated at 800 rpm for 30 s, followed by baking at different temperatures (75 °C for 120 s, 105 °C for 120 s, and 125 °C for 180 s). Later, the substrate was exposed to UV using a mask aligner (EVG 620 mask aligner, St. Florian am Inn, Austria) and developed using AZ300MIF to create the patterns. The photoresist pattern opening is used as the mold to electroplate nickel. The photoresist pattern and the electroplating conditions were optimized based on uniformity and morphology. The electroplating parameters such as current, temperature, and electrolyte composition are crucial in controlling the grain size, uniformity, composition, and mechanical properties. The nickel seed layer was deposited by connecting a patterned wafer as a cathode and a nickel plate as an anode. The 10 mA/cm^2 current density was applied for 5 min using nickel chloride as the electrolyte. Nickel striking was used to clean the base material and deposit a thin nickel layer for good adhesion. After depositing the nickel seed layer, the nickel was electroplated using the commercial nickel sulfamate bath solution at 55 °C. The electroplating was performed using the pulse current density of 10 mA/cm^2 with a duty cycle of 50% (10 ms off, 10 ms on) for 7 h. Nickel is electroplated slowly in the photoresist mold until the desired thickness is achieved. The photoresist layer was then stripped using acetone. After fabricating the bottom layer, micro saw teeth (top layer) were microfabricated using a similar technique as the one used to fabricate the base layer. The AZ 40XT photoresist was spin-coated on the surface, and nickel was baked at the temperature described above. The photomask of the top layer was manually aligned with the base layer and exposed to UV using EVG aligner. The pattern was developed in the developing solution and electroplated to create the top layer of the micro saw. The micro saws were released from the silicon substrates, etching the underneath gold layer. The potassium iodide solution was used as a gold etchant.

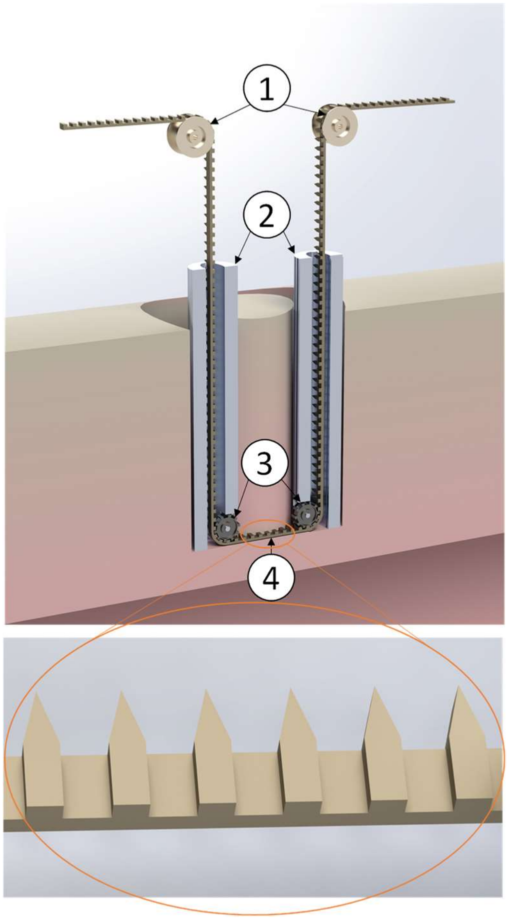

Figure 2. CAD model of donor root-side cutting mechanism showing (1) micro chainsaw guides inserted in donor profile (drilled), (2) pulley, (3) saw driver, and (4) micro saw (bottom) zoomed view of micro saw in action.

2.4. Materials Characterization

The surface morphologies of the samples were probed using a Zeiss ultra 55 scanning electron microscope (SEM) system (Carl Zeiss SMT GmbH, Oberkochen, Germany) operated at 5 keV. Samples were positioned at a 5 mm working distance to take SEM images. EDX (energy dispersive X-ray) microanalysis of the samples was performed at an acceleration voltage of 15 keV and at a working distance of 15 mm. The fabricated micro saw, and the micro saw driver were profiled using 3D optical microscope images (Keyence VHX-2000, KEYENCE Corp., Osaka, Japan). The mechanical properties of the samples were evaluated using a KLA iMicro nanoindenter system equipped with a three-sided Berkovich indenter. The tests were conducted on the upper side of the samples, at least 20 μm away from the edges, with a maximum indentation depth of 1 μm, which is less using a similar technique as the one used to fabricate the base layer. The AZ 40XT photoresist was spin-coated on the surface, and nickel was baked at the temperature described above. The photomask of the top layer was manually aligned with the base layer and exposed to UV using EVG aligner. The pattern was developed in the developing solution and electroplated to create the top layer of the micro saw. The micro saws were released from the silicon substrates, etching the underneath gold layer. The potassium iodide solution was used as a gold etchant.

than one-tenth of the sample thickness. A total of 25 nanoindentation data points were obtained at each location of the sample, with a strain rate of 0.05 s^{-1}, and thermal drift lying within 0.05 nm/s.

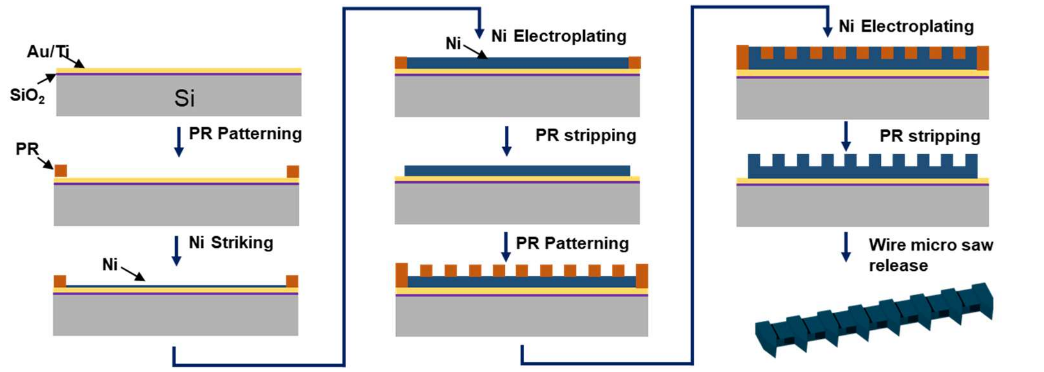

Figure 3. Schematic illustration of micro saw fabrication process.

2.4. Mechanical Characterization

The surface morphologies of the samples were probed using a Zeiss ultra 55 scanning electron microscope (SEM) system (Carl Zeiss SMT GmbH, Oberkochen, Germany) operated at 5 keV. EDX (energy dispersive X-ray) microanalysis of the sample was performed at an acceleration voltage of 15 keV and at a working distance of 15 mm. The 3D optical microscope images (Keyence VHX-2000, KEYENCE Corp., Osaka, Japan). The mechanical properties of the samples were evaluated using a KLA iMicro nanoindenter system equipped with a three-sided Berkovich indenter. The tests were conducted on the upper side of the samples, at least 20 μm away from the edges, with a maximum indentation depth of 1 μm, which is less than one-tenth of the sample thickness. A total of 25 nanoindentation data points were obtained at each location of the sample, with a strain rate of 0.05 s^{-1}, and thermal drift lying within 0.05 nm/s.

3. Results and Discussion

3.1. Morphology and Chemical Analysis

To analyze the morphology of the fabricated micro saw, SEM and 3D optical microscopy were performed. Figure 4A,B show SEM images of a top and bottom view of the micro saw. It is clear from the SEM images that well-defined high-resolution micro saws were fabricated. The SEM images (Figure 4A,B) show that the micro saw's cutting direction is perpendicular to its travel direction. The unique design of the fabricated micro saw will enable root-side cutting of the bone. The thickness of the base layer and micro saw tooth thickness measured using a 3D microscope were 85 ± 4 μm and 63 ± 3 μm, respectively (Figure S1). Figure 4C shows a 3D optical microscope image showing micro saw tooth anatomy. The saw has a tooth height of 250 microns, a tooth wedge angle of 54 degrees, a space of 250 microns between teeth, and a saw width of 500 microns. The pitch of the micro saw is 4 teeth per mm with an average thickness of 85 ± 4 μm. Micro saw anatomy was designed based on the requirement for symmetry, which is needed for optimal oscillating cuts [28]. Figure 4D shows the photograph of the fabricated micro saw, and the dimensions were compared with the US quarter coin. The dimension of the micro saw was 5 cm × 750 μm × 148 μm. EDX (energy dispersive X-ray) microanalysis of the micro saw presented in Figure 4E showed distinct peaks at 0.85 KeV and 7.47 KeV, which correspond to the L_α and K_α lines of nickel. The result confirms that high-purity nickel is electroplated on the Au/Ti deposited silicon wafer.

3.2. Mechanical Analysis

Figure 5 presents the elastic modulus and hardness values obtained from nanoindentation force-depth curves using the Oliver–Pharr method [29] at three different areas (A, B, C) on the surface of the micro saw. The testing areas were selected as representative spots on the sample, with A located near the left or right side, B near the top or blade of the sample, and C in the middle. The elastic modulus values of the three spots were 211 ± 2.51 GPa, 210 ± 1.79 GPa, and 212 ± 1.51 GPa, respectively. The corresponding hardness values were 6.76 ± 0.09 GPa, 6.87 ± 0.10 GPa, and 6.83 ± 0.07 GPa, respectively. These results show less than 1% deviation in the mechanical properties, indicating that homogeneous electroplating was conducted on the overall specimen. The absolute values of elastic modulus and hardness obtained in this study are consistent with previous researches [30,31], indicating that the mechanical properties of the fabricated micro saw are within the expected range for the material. The average elastic modulus and hardness of the human bone are in the range of 11 to 22 GPa and 0.2 to 0.7 GPa, respectively [32–34]. The mechanical properties of the fabricated micro saw are almost an order of magnitude higher than that of human bone. In addition, high hardness value of nickel provides good wear resistance for sliding contacts, indicating the micro saw's bone cutting capability [35].

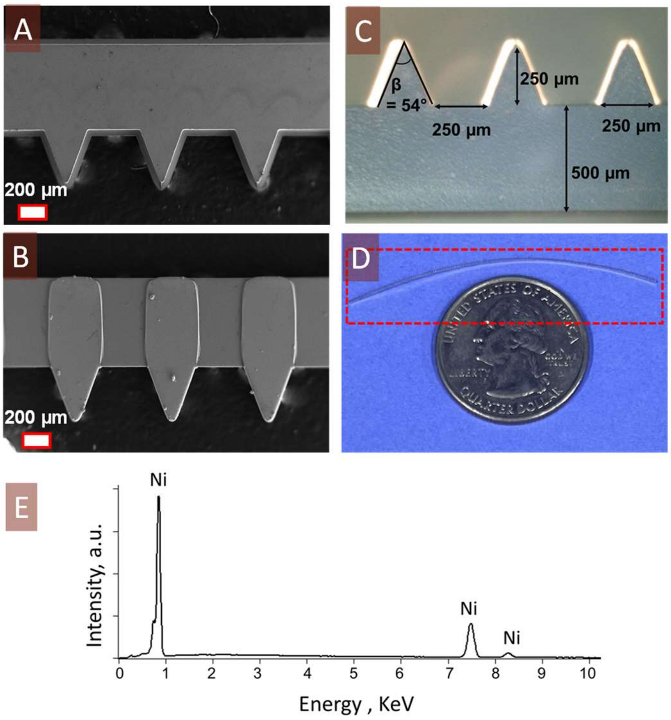

Figure 4. (**A**,**B**) SEM images of the fabricated micro saw bottom, and top view, (**C**) 3D optical microscope image showing micro saw tooth anatomy, β = wedge angle, (**D**) photograph of the fabricated micro saw size comparison with the US quarter coin, and (**E**) EDX analysis of the device.

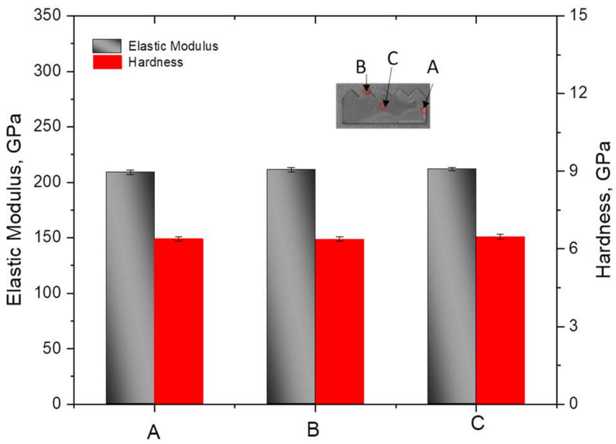

Figure 5. Elastic modulus and hardness of micro saw at areas A, B, and C, obtained using nanoindentation.

3.3. Bone Cutting Analysis

The CAD file of the micro saw blade holder and the setup were designed using solid works (Figure S2). The designed CAD models were printed using a 3D printer (Formlab 3B+). The home-built cutting setup was made using FUYU FSK30J Linear Actuator, Arduino Uno microcontroller, Newport linear stage, and L298N Motor Drive Controller Board. All these parts were assembled using 3D-printed structures. Later, the required electrical connection was made to power and control the step motor of the linear actuator. After building the setup, the Arduino microcontroller was programmed (Code S1) to move the linear actuator in a cutting motion at the desired degree of cutting speed. It is important to examine the performance of the fabricated saw for cutting the bone. To demonstrate the cutting capability of the fabricated micro saw, chicken bone was clamped and cut using the micro saw. The bone cutting setup and fully cut bone are shown in Figure 6A–C. The feed rate was manually controlled using a micrometer of the linear translation stage (Newport 433 Precision Linear Translation Stage). The maximum feed rate for the fabricated micro saw was 750 µm/min at the speed of 10 mm/s. If the feed rate exceeds 750 µm/min, the blade edge deformation and twisting of the saw were observed. The effect of the saw speed on strokes per mm^2 was evaluated at a constant feed ratio of 750 µm/min. A linear correlation was observed between the strokes/mm^2 and the saw cutting speed, as shown in Figure 6D. After analyzing the cutting performance, micro saw wear was morphologically examined using a microscopic technique. Since the micro saw was designed to be single-use, wear characteristics were examined before and after its single-use. Although bone debris (Figure S3) was found on the micro saw, no significant mechanical damage was observed, as predicted by the hardness testing results. In addition, to study the width and uniformity of the micro saw cut, an optical microscope image of the halfway-cut bone (Figure 6E,F) was analyzed. The width of the micro saw cut was 88 ± 3 µm with a smooth bone cross-section. These testing results suggest that the fabricated micro saw can be potentially used for root-side bone cutting.

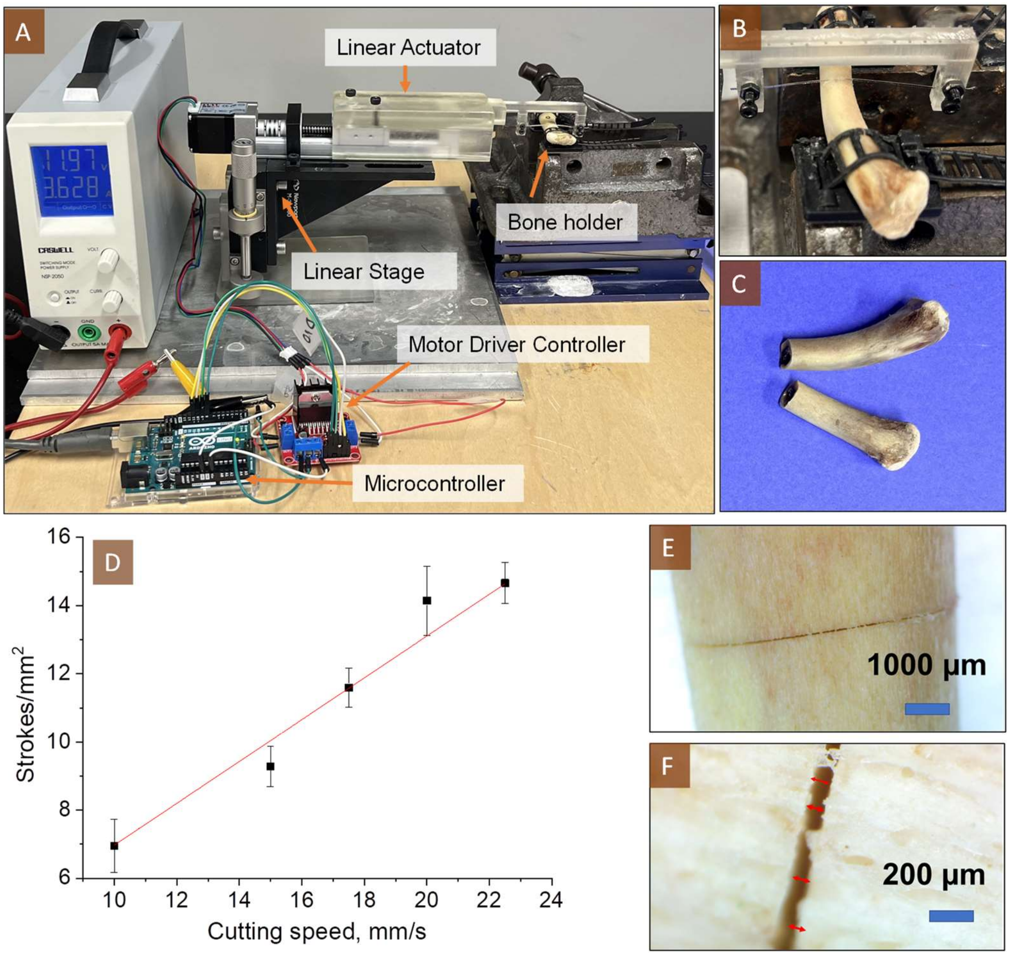

Figure 6. (**A**) Bone cutting setup, (**B**) a zoomed view of micro saw in action, (**C**) a picture of the bone showing uniform cutting, (**D**) number of strokes per unit area vs. cutting speed, and (**E**,**F**) optical microscope images of a bone cut at different magnification showing the uniform sub-100-micron wide cut.

4. Conclusions

The novel micro saw with integrated micro saw driver teeth was successfully fabricated using photolithography and electroplating. One of the critical parameters is the mechanical strength of the fabricated micro saw; the indentation test of the fabricated micro saw shows the hardness and the elastic modulus of 211 GPa and 6.75 GPa, respectively; these values are an order of magnitude higher than that exhibited by the human bone. For the root-side cutting of the donor without damaging the adjacent bone or cartilage, the micro saw needs to travel through a pair of guide tubes along the donor profile cut (1 mm or less). The fabricated micro saw with the integrated micro saw driver teeth is 750 µm in width with 148 µm thickness which is small enough to meet such a requirement. The width of the straight cut on an animal bone as small as 88 µm was demonstrated. The rotation or oscillation direction of the micro saw is designed to be perpendicular to the cutting direction; the fabricated micro saw can provide transverse cutting of the bone to extract a preoperatively planned bone-cartilage donor. This paper investigates the micro saw design and fabrication, providing future research directions for a robotic automated osteochondral tissue harvesting method. The proposed robotic tissue harvesting method can remove virtually any shape and size of complex donor grafts for autograft transplantation to treat severe osteoarthritis.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/mi14040856/s1, Figure S1: 3D optical microscope images of saw and saw driver; Figure S2: CAD model of 3D printed part used to build test setup; Code S1: Arduino code used for controlling the linear actuator; and Figure S3: Optical microscope images of saw blade tooth surface before and after cutting bone.

Author Contributions: H.J.C., S.-E.S. and P.P. conceived and designed the experiments; P.P., J.F. and Y.-C.K. performed the experiments and analyzed the data; P.P., S.-E.S., Y.-C.K. and H.J.C. wrote the manuscript; S.-E.S. and H.J.C. supervised the project. All authors have read and agreed to the published version of the manuscript.

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Design and Fabrication of Micro Saw for Osteochondral Autograft Transplantation

Abstract

Introduction:
Osteoarthritis (OA) is the most common joint disorder, affecting nearly 529 million population (2019) worldwide. It typically occurs in lower and upper limb joints and begins to break down the cartilage connecting the joints. Since cartilage does not contain blood vessels, lymphoid tissue, and nerves, it makes the healing process difficult. Thus, surgical intervention is an inevitable solution. The surgical treatment method involves transplanting small cylindrical bone-cartilage plugs to refill the affected site in the same patient, known as Mosaicplasty, an autologous transplantation procedure. The technological limitation of this procedure is tightly filling prepared defect area with multiple healthy osteochondral donor plugs. To overcome this limitation, a bone cutting mechanism that can harvest a predetermined donor shape is required, especially for cutting root-side of the donor instead of cracking out many small plugs. Here, we present a preliminary design and fabrication of a novel micro saw mechanism utilizing transversal blades that can extract a preoperatively planned bone-cartilage donor for autologous transplantation to treat severe osteoarthritis.

Materials and Methods:
Electroplating can be employed as one of the micromachining technologies when combined together with photolithography to make miniaturized devices with various types of metals such as nickel, gold, silver, copper, and their alloys. Electrical, mechanical, and magnetic characteristics, as well as chemical homogeneity of the metal layer, are the main parameters to control for a high-performance component. Therefore, it is critical to control, optimize, and standardize the fabrication parameters. In order to fabricate the micro saw with transversal blades, resembling a miniature timing belt with sideway blades, an electroplating process combined with two-step photolithography was used. The micro saw was designed with a simple structure without a mechanical connector to maximize its lifetime. Multiple micro saw segments were fabricated using a 3-inch oxidized silicon wafer. First, Au/Ti thin film was deposited using e-beam deposition. Then, the AZ 40XT photoresist was spin-coated at 800 rpm for 30 sec and baked at 75℃ for 120 s, at 105℃ for 120 s, and at 125℃ for 180 s. Later, the substrate was exposed to UV using an EVG aligner and developed using AZ300MIF to create the patterns. The nickel seed layer was electro-deposited on the exposed area using a 10mA/cm^2 current density for 10 min. The nickel seed layer acts as a nucleation layer and provides the conducting path for electroplating. Nickel plating was done using a commercially available nickel sulfamate electroplating solution. The plating process was conducted by using a pulse current of 10mA/cm^2 with a duty cycle of 0.5 at 55℃. In this process, the photoresist pattern was used to create the metallic structure, and later it was removed using acetone. After fabricating the bottom layer, a similar process was used to fabricate the top layer for micro saw driver teeth. Finally, micro saw segments were separated from the silicon substrate by etching underneath Au/Ti layer. The thickness of the fabricated nickel micro saw is 200 microns, which makes it flexible, allowing the micro saw to bend along the cut with the desired degree of curvature. We have also designed

and fabricated micro saw drivers to engage the micro saw during its operation using the same fabrication steps as the blades.

Results:

A novel nickel micro saw prototype is fabricated using the photolithography technique in combination with electroplating to be able to extract a personalized autograft from a donor site for osteochondral autologous transplantation. The fabricated micro saw has the saw teeth aligned perpendicular to the direction of the micro gear teeth to cut the root-side of the doner. In addition, the thickness of the micro saw ~200 µm with 750 µm in width was achieved suitable for operating within a small drilling path, less than 2 mm. The fabricated parts were visually inspected by 3D optical microscopy, showing the successful fabrication of the micro saw and the micro saw driver. Micro indentation was performed to derive mechanical properties for evaluating the integrity of the fabricated micro saw. The elastic modulus and hardness values of the micro saw are 209 ± 2.04 GPa and 6.39 ± 0.0940 GPa, respectively, which are about an order of magnitude higher than those exhibited by human bones. To demonstrate the cutting capacity of the micro saw, we designed a micro saw holder using a 3D printer and demonstrated the cutting of chicken bones.

Conclusion:

The novel micro saw with integrated micro saw driver teeth was successfully fabricated. The flexibility and bone-cutting capacity of the micro saw is demonstrated. For cutting the root-side of the donor, the micro saw needs to travel through a pair of guide tubes along the donor profile cut (2mm or less). The fabricated micro saw with integrated micro saw driver teeth is 750 µm in width with 200 µm thickness which is small enough to meet such a requirement. The rotation or oscillation direction of the micro saw is designed to be perpendicular to the cutting direction, the fabricated micro saw can provide transverse cutting of the bone to extract a preoperatively planned bone-cartilage donor for autologous transplantation that can treat severe osteoarthritis.