Electrically Zipping Bending Actuators for Prosthetic Fingers

Tristan Fraai, Jian Wen, and Majid Taghavi

***Abstract*—State-of-the-art prosthetics use traditional 'muscle-tendon' systems to flex and extend fingers. The main consumer complaint is the weight of a prosthetic, aggravated by this complicated mechanism. This letter introduces an electrically zipping bending actuator (EZBA), a soft actuator that fuses structure and function into one component, reducing the weight of a single bending actuator to 2.5g. These actuators use the dielectrophoretic liquid zipping (DLZ) actuation concept, employing an amplified electrostatic force to attract two thin insulated electrodes. Holding the bottom strip in place and moving the tip of the top strip backwards creates a buckle, a crucial part of creating a bending movement using electrostatic attraction. During actuation, the buckle decreases in size and pushes the top end of the EZBA downwards and bends the whole structure. To evaluate the actuator's performance, tip bending and generated force were measured and compared to those achieved by a human finger. The actuator bent to 89.6° (45.8mm) and achieved a grip force of 177 mN.**

***Index Terms*—Prosthetics and Exoskeletons, Rehabilitation Robotics, Soft Sensors and Actuators, Wearable Robotics**

I. INTRODUCTION

Reintegration of amputees into society relies on current state-of-the-art robotic prosthetics. However, flaws in these prosthetics still hinder this process. The main consumer complaint is the prosthetic's weight [1]. For example, one finger of the BeBionic v2 Prosthetic Hand weighs 38g, including its relevant gears and motor [2]. This weight may be increased due to the large component count of the traditional finger actuation mechanisms. These mechanisms use a 'muscle-tendon' inspired approach where cables and pulleys simulate tendons and a standard DC motor acts as a muscle, pulling on tendons to flex or extend a finger [3].

To reduce component count and weight, and increase their compliance, current research focuses on soft actuators, such as soft pneumatic actuators, dielectric elastomers and hydraulically amplified electrostatic actuators. Pneumatic actuators require large and complicated energy resources and control units, often with considerable noise [4]. Dielectric elastomers lack sufficient force, exhibit unreliable consistency, and involve a complex manufacturing process [5]. Hydraulically amplified electrostatic actuators use encapsulated dielectric liquid, increasing weight and the risk of leaking [2], [6], [7]. This letter presents a new type of electric bending actuator that uses a lightweight dielectrophoretic liquid zipping (DLZ) actuation concept to directly bend the fingers. By employing a dielectric liquid, such as silicone oil, in the joint where two oppositely charged strips meet, they 'zip' closed when a current passes through them. The attraction strength is amplified by the dielectric liquid. DLZ enables embedding the required functional structure in the monolithic actuation unit, allowing bending without any extra components. The main contribution of this approach is its ability to significantly reduce the overall size and weight of robotic prosthetics while simplifying the integration of soft actuators into the design.

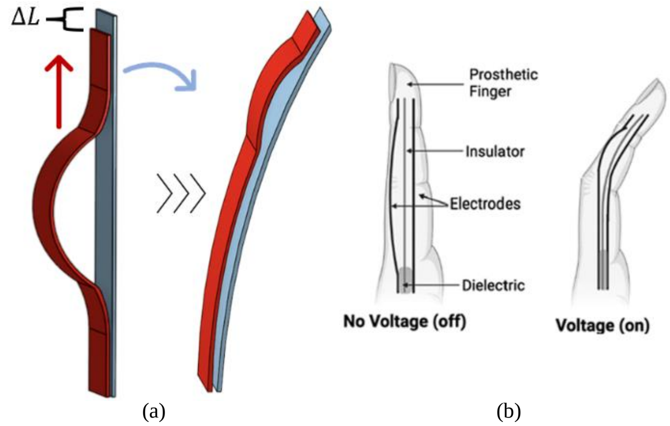

Fig. 1. (a) A 3D model of EZBA transitioning from rest to contraction, with coloured arrows indicating the hypothesised motion of each sheet during actuation. (b) A diagram showing the use of EZBA in a finger.

DLZ has been shown to apply linear force directly through the electrode and insulator [8], using efficient, silent, and easily controllable electrostatic force. The generated electrostatic force is significantly amplified, theoretically up to 120-fold, by using a dielectrophoretically-driven bead of dielectric liquid, enabling lightweight and high-strain actuators [8].

In this letter, we introduce a new design of the DLZ actuators, Electrically Zipping Bending Actuator (EZBA), which allows for direct bending rather than linear contraction. EZBA consists of two PVC-insulated steel strips stacked together with the top strip slightly pushed back to create a small buckle (Fig. 1). We measured buckle size by the difference in tip length when pushing the top strip back (ΔL) and investigated the buckle size's impact on the generated displacement and force. We observed using a stiffer strip for the top electrode and a more compliant strip for the bottom electrode further aids in bending. The stiffness of the strips was varied to investigate its effect on displacement and force.

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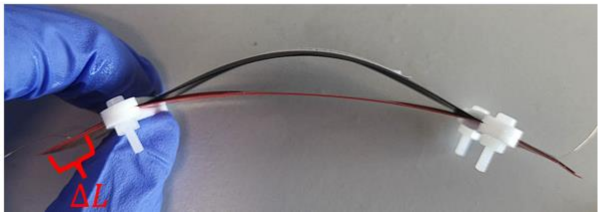


Fig. 2. Typical EZBA with a 5mm tip difference and its resulting buckle.

II. Method

A. EZBA Development

The EZBA was made using the same material as electro-ribbon actuators [10]. This consists of cutting two thin steel sheets (1.1274 carbon steel, h+s Präzisionsfolien GmbH, Germany) to 100mm. The thickness varied from 30-90µm. A copper wire was soldered to one end of each strip, and then both sides of the steel sheet were insulated with PVC tape (AT7, Advance Tapes, UK). To clamp the two electrodes, a PLA-based 3D printed clip was used, held with plastic screws. For force amplification, a few drops of 50cSt silicone oil (378356, Sigma-Aldrich, USA) were applied at the pinch points before running the experiments.

B. EZBA Design

In contrast to electro-ribbon actuators, EZBA is made with misalignment between two layers to create a buckle. The top and bottom layers are clamped together at one end, while the other ends are displaced by ΔL (2mm, 5mm, 10mm, 15mm, or 20mm), along the strip and then clamped together.

Fig. 2 shows how a typical EZBA uses the buckle to pre-bend its structure. The electrostatic force between the layers causes them to zip together and move the buckle inwards, which leads to the whole structure bending. It implies that the stiffness of the layers, and the original buckle shape (related to ΔL) determine both the initial elastic energy stored and its bending capacity, and therefore, have a direct effect on the generated bending force driven by the electrostatic force. The electrostatic force can subsequently be modelled as two variable capacitors in series [10], which both influences and depends upon the deflection of the electrodes. Design dimensions and function parameters including voltage and current are summarised in Table I.

C. Experiments

For the isotonic characterisation, a Keyence laser displacement sensor in Fig. 3(a) was used to accurately measure the downward motion of the EZBA's tip. Fig. 3(b) shows the setup used for the isometric characterisation to measure the force exerted at the tip. A 5N load cell (900 Series, Richmond Industries Limited, UK) was fixed above the EZBA, and a clip with a hinge joint ensured normal force measurement. A clamp held the bottom of the EZBA in place to better simulate palmar flexion. All data were collected with MATLAB, using a National Instrument I/O terminal to read data from the laser and load cell.

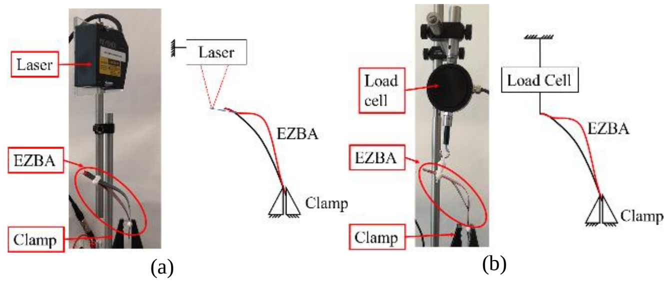


Fig 3. Experimental setup. (a) Isotonic characterisation for displacement measurements; (b) Isometric characterisation for force measurements.

TABLE I
Design and Function Parameters

Electrode Dimensions (mm)		**Operation**	
Width	12.7	Voltage	1-7kV
Length	100	Current	10-50µA
Thickness	0.03-0.09		

The displacement analysis explored different buckle sizes (2mm, 5mm, 10mm, 15mm, or 20mm) and three thickness configurations: 30/70µm, 50/70µm, and 50/90µm (first number for bottom electrode thickness, second number for top electrode thickness). Frequency response studies were also conducted from 1 to 6 Hz, with a 1 Hz interval between measurements.

The two highest displacing buckle sizes were selected for force analysis, while maintaining all three thickness configurations. This approach aimed to strike a balance between displacement and force and, therefore, achieve a well-balanced total configuration among the tested values.

Each data point for displacement and force measurements represents the average and standard deviation of five trials. Table II summarises the experimental design parameters for both displacement and force experiments.

TABLE II
Displacement and Force Experimental Design Table

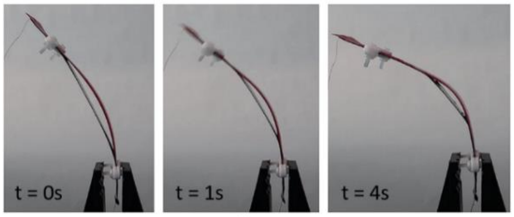
Variables to test displacement (mm)	**Variables to test force (N)**
Thickness (30/70, 50/70, or 50/90 µm)	Thickness (30/70, 50/70, or 50/90 µm)
Voltage (2-8kV)	Voltage (2-8kV)
Tip length difference (ΔL = 2, 5, 10, 15, or 20mm)	Tip length difference (ΔL = 2 or 5mm)

An additional investigation was conducted to determine the weight capacity of the EZBA at different bending positions. Loads of 3.5g, 5.5g, and 7.5g were applied to the tip of the EZBA at angles of 70°, 90°, and 110°. Additionally, passive displacements were recorded when the tip was loaded with 4g, 5g, 6g, and 7g weights.

III. Displacement Results and Discussion

A. Initial Displacement Investigation

Fig. 4 shows the general progression of an EZBA during zipping actuation when a voltage is applied to the actuator. The EZBA begins zipping through both ends, pushing the



(a) (b) (c)

Fig. 4. Image sequence of an actuated EZBA (50/70μm, 6kV, ΔL = 5mm). (a) The actuator at rest; (b) The initial contraction at the first second; and (c) The contracted EZBA after 4 seconds.

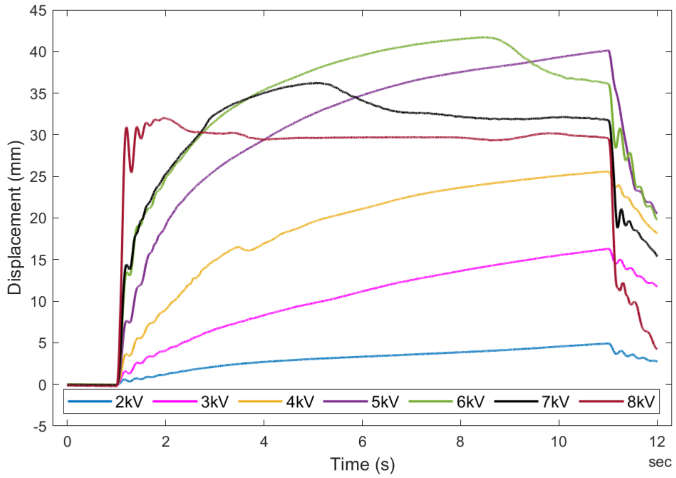


Fig. 5. Displacement over time according to changes in voltage, using a tip length difference (ΔL) of 5mm and a thin (30/70μm) actuator.

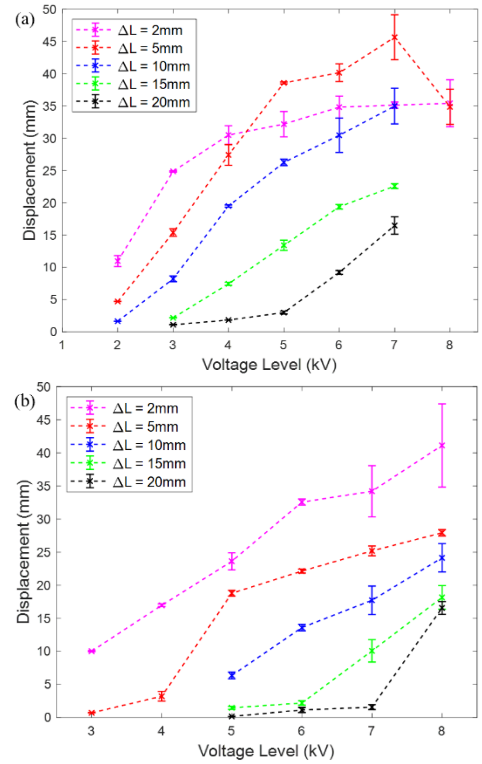
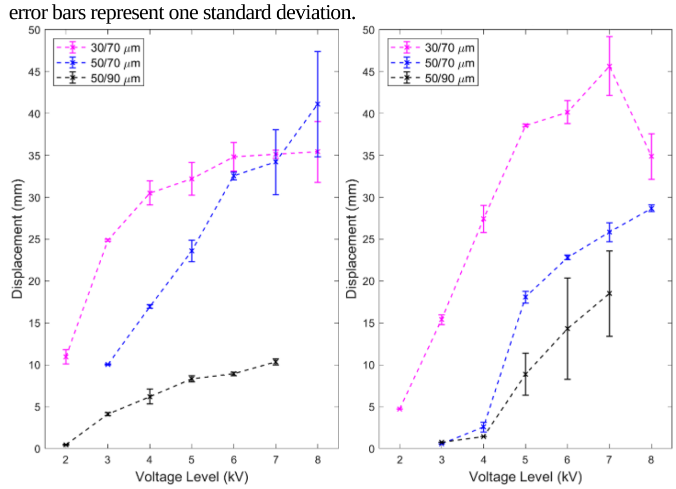


Fig. 6. Tip displacement resulting from varying input voltage for (a) the thinnest (30/70μm) actuator, and (b) the medium (50/70μm) thickness actuator, at different tip length differences. Displacement is shown as 96% of the maximum value, and error bars represent one standard deviation.



(a) (b)

Fig. 7. Tip displacement for the three different configurations at tip length differences of (a) 2mm, and (b) 5mm. Displacement is shown as 96% of the maximum value, and error bars represent one standard deviation.

bead of dielectric liquid further along the length of the actuator. The zipping of the pinch points causes the buckle to decrease in size and pushes the tip of the actuator downwards. This zipping continues to a critical point at which the EZBA cannot zip further and remains bent for the duration of the signal. When the voltage is turned off, the EZBA snaps back into its resting configuration from the elastic recoil stored in the bent beams.

Fig. 5 shows the displacement of the actuator tip when different voltages from 2kV to 8kV are applied. Higher voltages, up to 6kV, lead to a faster response time, defined as the time taken to contract to at least 96% of the maximum displacement, and a higher contraction. A high voltage signal causes significantly faster response time, sometimes reaching a maximum as soon as two seconds, but this comes with a concession in terms of displacement, as values decrease after a quick contraction. Therefore, consecutive displacement and force values are reported at 96% of their stable maxima. At 7kV and higher, the voltage is too strong and sometimes leads to a different actuation behaviour that will be discussed later.

Fig. 6 displays a comparison between different buckle sizes, achieved by varying the tip length difference ΔL, for the thin (30/70μm) and medium (50/70μm) actuators. Both graphs show that a ΔL of 2mm and 5mm performs the best, routinely achieving higher displacement values compared to any other buckle sizes. However, increasing ΔL to 15mm or 20mm results in much smaller bending. We attribute it to the size of the initial zipping angle in the buckle since a smaller angle between two zipping electrodes allows for the two layers to be closer together, creating a stronger attractive force.

B. Comparing Thickness at Optimal Tip Length Difference

Using these results, we compared different thickness levels at 2mm and 5mm ΔL (Fig. 7). The thin actuator achieved the highest displacement, 45.8mm, at 5mm ΔL and 7kV.

The displacement values can be converted into approximate angles to compare with human finger bending. As 92mm is the total length of the EZBA that achieved 45.8mm contraction, this means that it bent 49.8%. Using the approximation that a 90° bend is achieved by bending to 50%, the EZBA achieved 89.6°. This is only 2.4° below the proximal inter-phalangeal joint's maximum [12]. Of the three joints of the finger, the proximal

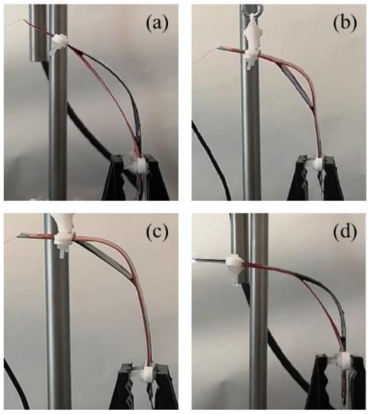


Fig. 8. Images demonstrating the 'let-go' effect experienced at high voltages (6-8kV). (a) EZBA at rest; (b) initial contraction, appearing regular with zipping from both the top and bottom end; (c) let-go from the top, with additional zipping at the bottom and an upwards displaced buckle; (d) let-go from the bottom, with additional zipping in the top and a downwards displaced buckle.

inter-phalangeal joint, which is the second from the wrist, bends the most at 92° [12]. For lower voltages, the thin actuator with a 2mm ΔL achieves larger displacement values than any other configurations between 2-4kV. This suggests that using a smaller buckle with a thinner bottom and thicker top layer is ideal for lower voltage displacement. Below 2kV, none of the current configurations displayed movement.

C. Buckling Behaviour and Actuation Dynamics

Interestingly, the smallest buckle did not perform the best, despite having the smallest zipping angles. This could be due to the 'let-go' effect, a phenomenon observed particularly at higher voltages (Fig. 8). The let-go effect occurs when zipping more on one side than the other and thus the unbalanced distribution of force causes the buckle to move upwards or downwards. We attribute it to the fact that the electrostatic zipping force opposes the elastic force stored in the buckle. When the buckle starts zipping from one side with a strong force, it fluctuates between two zipping points until the electrostatic force and the elastic force reach equilibrium. However, as it is easier to initially achieve a high degree of bending with a smaller buckle, it was seen that the angle between the two films increased during actuation. The increased angle then can cause asymmetric contraction, tipping the buckle away from equilibrium, which is then compromised by one strip 'letting go' and the other strip zipping further. This looks as if the buckle then moves upwards or downwards. The let-go was only experienced at higher voltages, particularly when ΔL was at 2mm. This suggests a trade-off between a smaller buckle and tolerance for higher elastic restorative forces.

We also investigated the effect of a single active zipping point in the buckle. The experiments consisted of inserting a small, thin acrylic layer at the top joint to prevent zipping at that corner and thus investigate bottom-only actuation, and vice versa for top-only actuation. At 6kV, the thin (30/70μm) actuator with ΔL at 5mm achieved 23.2mm for bottom-only, and 21.3mm for top-only bending. When free to bend from both sides at the same time, the EZBA reached just over 40mm, demonstrating that both zipping points contribute to bending.

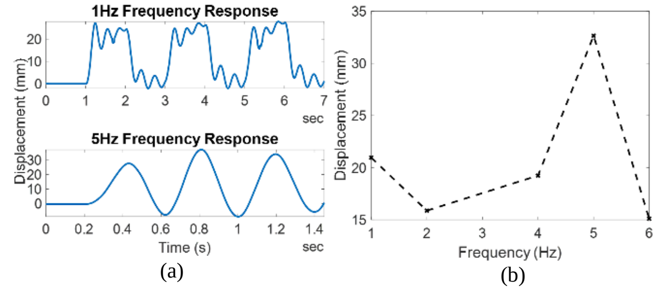


Fig. 9. Frequency responses tested on a 30/70μm actuator at 6kV with 5mm tip length difference for (a) 1 Hz and 5 Hz that appeared to reach a resonant frequency, and (b) comparison of the averages of the first peaks for each frequency response.

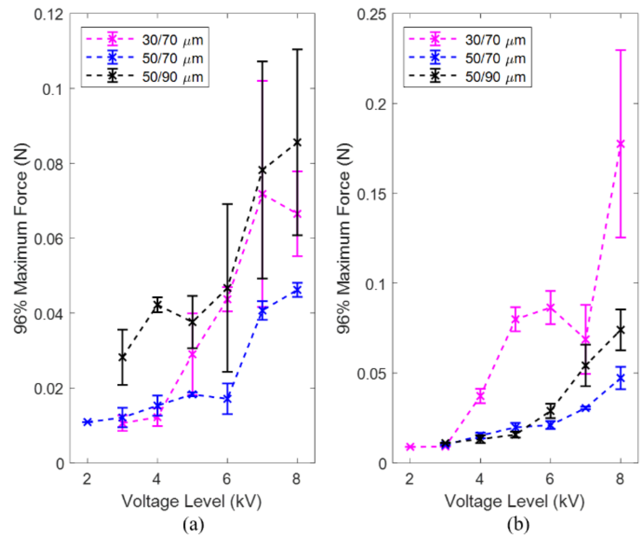


Fig. 10. Force generated by the three configurations for the tip length differences of (a) 2mm and (b) 5mm. Force is shown as 96% of the maximum value. Error bars represent one standard deviation.

Fig. 9(a) shows the frequency responses of the EZBA to investigate its dynamics for potential uses in periodic movements. The displacement lingers around the same value (approximately 19mm) as frequency increases. However, at 5Hz there is a significant increase above this, where displacement reaches approximately 32mm. This suggests that 5Hz may be closer to the resonance frequency of the device, where its elastic response almost matches the electrostatic response.

IV. Force Results and Discussion

A. Initial Force Investigation

Fig. 10 shows the result of force characterisation. For the combination of thicknesses and the buckle sizes tested, the thin actuator with 30/70μm and 5mm ΔL configuration achieved the highest force of 0.1775N at 8kV. The 5mm ΔL might enable higher forces by reducing let-go during contraction, allowing the actuator to maintain continuous force pressure. The thin actuator with ΔL at 2mm generated less force than the thick (50/90μm) actuator, although due to high standard deviation, this is inconclusive. The large uncertainty of values arises due to the combined effect of let-go and small forces produced by the actuator. They vary in the range of 10^{-2}, inherently increasing error.

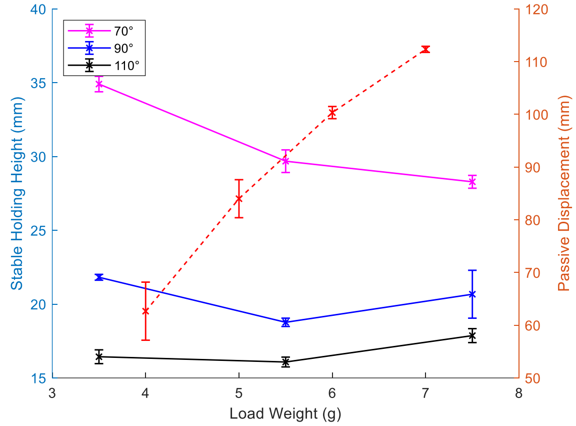


Fig. 11. The heights at which EZBA were able to maintain specified weights (Left axis); The compression of EZBA under different weights, shown as a dashed line plot (Right axis).

Comparing the highest force values achieved by EZBA to that of the human finger reveals the need for technology improvement to exert a higher force. The dominant index finger during palmar flexion can achieve values up to 27.9N, nearly 160 times larger than the current EZBA [13]. Inclusion of dynamic stiffness control in splinted designs needs to be investigated in future studies to enhance the generated force for implementation in a prosthetic finger.

B. Stable Holding Height

Fig. 11 shows the effect of displacement on actuation force and its passive displacement for the 30/70µm EZBA at 8kV. We loaded the fingers at bending angles of 70°, 90°, and 110°, allowing them to relax and attain equilibrium between electrostatic and potential energy. The left axis shows where the fingers can maintain a stable grip under different loads, resisting a return to their fully opened resting position. The load-holding capacity is higher for the EZBA when it bends further, indicating a stronger electrostatic zipping force due to the increased contact area. The right axis represents the passive movement of the fingertip under different loads when voltage is off, demonstrating a nearly linear relationship between the applied force and its displacement.

C. Comparison with Other Actuators

The thin actuator using a 5mm ΔL has been measured as the best EZBA, offering no compromise between force and displacement. Equations (1) and (2) were used to calculate its specific power and energy:

$$Specific\ Power = \frac{F \times d}{t \times m} \quad (1)$$

$$Specific\ Energy = \frac{F \times d}{m} \quad (2)$$

Where F is the average normal force generated at the tip, d is average tip displacement, m is the total mass of the actuator, and t is the time taken to achieve the force and displacement values. The maximum specific power and specific energy values for a 30/70µm, 5mm tip displaced actuator at 6kV were 4.05 $W\ kg^{-1}$ and 2.06 $J\ kg^{-1}$, respectively.

For comparison with the soft electrostatic actuators, a bending dielectric elastomer actuator exerted forces of 2.1mN to 2.4mN at 3kV [14], and another up to 143mN at 6kV [15].

(a) (b)

Fig. 12. (a) A 3D printed model finger encapsulating the EZBA. (b) The proximal interphalangeal joint's bending capabilities.

A curling HASEL actuator achieved just over 80mN with a sine input at 0.1Hz of DC 5kV ± AC 5.5kV [16]. Conventional prostheses generate force at the fingertips, ranging from 9.9N to 24.9N [17]. The EZBA configurations tested here use only a single unit, incorporated into the finger structure, whereas it has been shown that multiple configurations can be used to increase both force and displacement [8].

The heaviest EZBA tested here was the thickest one, weighing approximately 2.5g, a steep decrease from the 38g of the BeBionic v2 Prosthetic Hand [2], although does apply lower force.

D. 3D Printed Model Finger

We integrated the EZBA with a 30/70µm configuration as a muscle into a 3D-printed model finger. As shown in Fig. 12, the finger bends once the voltage is applied, returning to an upright state when the actuator is relaxed. The EZBA achieved a bend of 89.6° during contraction, similar to the proximal interphalangeal joint's maximum of approximately 92° [12]. A supplementary video file, demonstrating the complete contraction cycle, will be available at http://ieeexplore.ieee.org. The EZBA begins zipping through both ends when voltage is applied, driving the finger's movement. Once it reaches a critical point, the EZBA cannot contract further, and the finger remains bent throughout the signal duration. When the voltage is turned off, the finger returns to its static state due to the elastic recoil force of EZBA. Although using a single EZBA unit in the finger, its actuation mimics the movement of human fingers, indicating its potential to be used in prosthetic applications.

V. Advantages, Limitations, and Future Investigations

DLZ actuators have demonstrated a self-locking function, allowing lower voltage signals to maintain contraction [9]. This capability could be ideally used in EZBA to keep the finger bent with much lower energy consumption. Incorporating the variable stiffness solutions can also be used in this scenario to extend the loading capacity applied on the bent finger. Self-sensing properties of the DLZ actuators [10] also eliminate the need for additional sensors to measure contraction. However, it needs to be adopted for the variable loads to demonstrate its practicality in EZBA when experiencing dynamic forces.

Although EZBA produced promising results, some limitations to the current investigation should be noted. The foremost limitation of the current EZBA design is its use of a dielectric liquid. The liquid remains at the zipping point by dielectrophoresis when the voltage is applied to the actuator.

When it is off, the bead of liquid sits there because of the surface tension, but it may drop off, causing uncertainty in the practical applications. Another limitation is that at larger buckle sizes (i.e. ΔL) zipping did not occur symmetrically from both ends. This is an important aspect, as squeezing the buckle from both zipping points increases the elastic energy stored in the strips, thus causing the actuator to bend and reach the equilibrium position. This asymmetric zipping issue mainly occurs because of the oil dripping from the top zipping point at larger buckles, causing in some cases no contraction at the top end of the EZBA. In situ oil reservoir solutions may be required for oil retention and to improve the repeatability of the bending actuator in real-world applications.

This paper studies the design of basic bending actuators using the DLZ actuation concept. To make it practically applicable in prosthetics, future investigations will focus on discretising the EZBA to study the three-phalange finger pattern. This approach will extend the number of active zipping points along the strips, thereby increasing the bending and loading capacity. By shortening the EZBA, the moment arm from which the joints bend decreases in length, resulting in increased torque generated at the tip. The current EZBA measures around 10cm in length, whereas if three EZBA were used in a single finger, 3-4cm long actuators would be sufficient. Using a shorter EZBA could also affect the overall contraction and thus it should be the subject of an all-encompassing investigation to minimise compromises and achieve efficient joints. An additional investigation into the stimulation pattern and synchronisation of several EZBA units in the finger needs to be conducted.

Lastly, EZBA relies on high voltage input although with an extremely low current (i.e. 10-50 µA). It necessitates insulating encapsulation of the actuator and the electronics which can be partially achieved by the prosthetic material. Meanwhile, we will explore replacing the insulator with a high-dielectric-constant and thin material in future works to maximise the performance of our actuator while operating at the lower voltages.

VI. Conclusion

We developed and characterised an electrically zipping bending actuator (EZBA) based on the dielectrophoretic liquid zipping concept. The best-performing actuator from the current investigation, both in terms of force as well as displacement, appeared to be the thinnest (30/70µm) actuator. It achieved a maximum displacement of 45.8mm, or 89.6°, at 7kV and using a tip length difference (ΔL) of 5mm. Compared to the maximum achievable value of a human finger (92°) [12], this is a satisfactory result for a single unit. When increasing the voltage to 8kV, the maximum force of 177mN is achieved in the same actuator configuration. However, this is 160 times less than the maximum force achieved by the dominant index finger (27.9N) [13]. EZBA shows a relatively fast response with the ability to operate at frequencies as high as 4 Hz. Due to its ability to fuse function into a structure, this lightweight bending actuator exhibits high potential for integration into prosthetic hands and manipulation applications.

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