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Contents

Preface to "Reconstructing the Iron Hands of knight Götz von Berlichingen and its derived modern developments"

In the beginning there was an idea: the reconstruction of the two Iron Hands of the Franconian imperial knight Götz von Berlichingen (1480-1562). We had not yet planned that this would become a new neuroprosthetic research field of its own at Offenburg University. We are therefore all the more pleased to be able to present to the interested reader in this book the wide range of new ideas that we have so far derived from the Iron Hands.

Andreas Otte

prosthesis

Editorial

Invasive versus Non-Invasive Neuroprosthetics of the Upper Limb: Which Way to Go?

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Abstract: In this editorial, a topic for general discussion in the field of neuroprosthetics of the upper limb is addressed: which way—invasive or non-invasive—is the right one for the future in the development of neuroprosthetic concepts. At present, two groups of research priorities (namely the invasive versus the non-invasive approach) seem to be emerging, without taking a closer look at the wishes but also the concerns of the patients. This piece is intended to stimulate the discussion on this.

Keywords: neuroprosthetics; upper limb; invasive; non-invasive; augmented reality; 3D printing; finite element method; computer-aided design

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If we had a time machine and could travel to the year 2040, we would certainly be in a better position to decide which way — invasive or non-invasive — would have been more appropriate for developing intelligent neuroprosthetic approaches of the upper limb. The work of Ortiz-Catalan et al., for example, recently published in the *New England Journal of Medicine*, is undoubtedly very impressive [1]: In four patients, the authors presented an implant that was anchored to the humerus through osseointegration, allowing for bidirectional communication between a prosthetic hand and electrodes implanted in the nerves and muscles of the upper arm.

Whether this method will in future be the method chosen by the majority of patients and, if at all, paid for by health insurance companies, is open to discussion [2,3]. Certainly, simpler, non-invasive approaches should be considered, such as electrode-free visual control of the prostheses with augmented reality (AR) glasses [4] and providing the user with sensory input in a different, non-invasive way: Marasco et al. [5], for instance, integrated kinesthetic feedback in three hand amputees by vibrating the muscles used for prosthetic control via a neural-machine interface, improving movement control within few minutes. Last but not least, today's inexpensive multi-material 3D printing offers the possibility of producing personalized prostheses based on design data, 3D scans, or magnetic resonance imaging data. Physical models implemented by computer-aided design (CAD) using the finite element method (FEM) analysis also allow for developing improved mechanical components of existing or planned prostheses (Figure 1).

Already 20 years ago, there were many approaches to control prostheses with electrodes, mainly via electromyography or electroencephalography signals. Electrodeless control via AR glasses did not exist at that time, since the development of the AR glasses was still in its infancy, and 3D printing was also just in the beginning stages. Today, however, we can cost-effectively incorporate both 3D printing and AR glasses into our thinking about developing novel smart neuroprostheses.

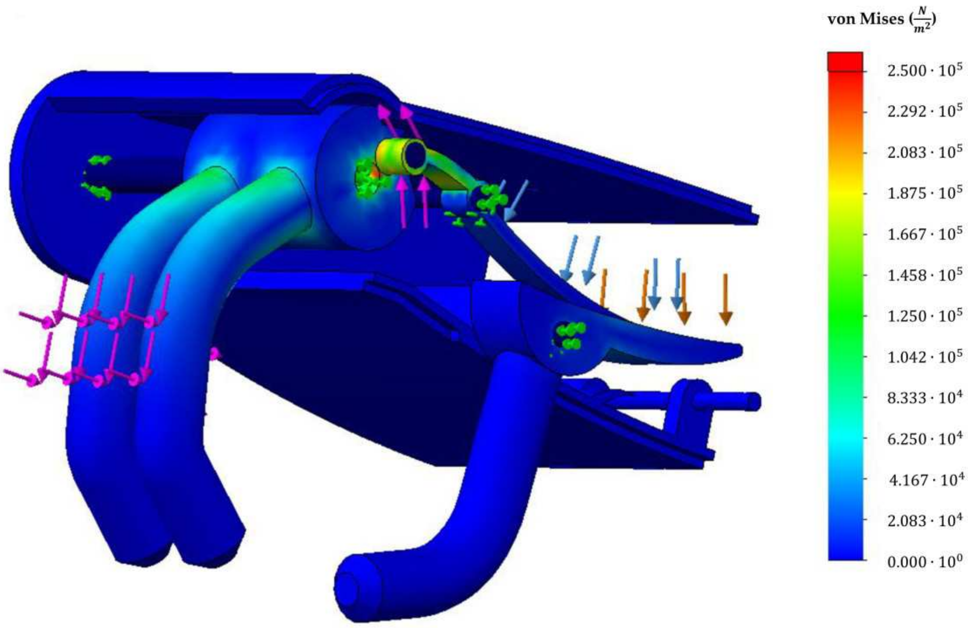

Figure 1. Finite element method (FEM) analysis of a part of the CAD-reconstructed historical first hand prosthesis of Götz of the Iron Hand (Götz von Berlichingen 1480–1562) [6–8]: The analysis shows increased forces mainly in the thumb lever; the maximum stress of this analysis is about $2.5 \times 10^5\ \frac{N}{m^2}$ (von Mises).

Maybe in 20 years, we will say that it would have been good to combine both approaches, i.e., ideas from the invasive approach with ideas from the non-invasive approach. Parallel development of these, without looking at the other idea, as we currently deem to observe, is probably the wrong move. The degree of invasiveness is ultimately determined by the possibilities that the non-invasive approaches will provide. The more convincing non-invasive approaches we develop, the better. The lynchpin should ultimately be the user, depending on various factors such as age, health status, financial status, etc. Akin the situation with deep-brain stimulation [9], it would be the onus that an open dialogue between engineers and physicians should take place for the development of neuroprosthetics of the upper limb.

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prosthesis

Review

3D Computer-Aided Design Reconstructions and 3D Multi-Material Polymer Replica Printings of the First "Iron Hand" of Franconian Knight Gottfried (Götz) von Berlichingen (1480–1562): An Overview

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Abstract: Knight Götz von Berlichingen (1480–1562) lost his right hand distal to the wrist due to a cannon ball splinter injury in 1504 in the Landshut War of Succession at the age of 24. Early on, Götz commissioned a gunsmith to build the first "Iron Hand," in which the artificial thumb and two finger blocks could be moved in their basic joints by a spring mechanism and released by a push button. Some years later, probably around 1530, a second "Iron Hand" was built, in which the fingers could be moved passively in all joints. In this review, the 3D computer-aided design (CAD) reconstructions and 3D multi-material polymer replica printings of the first "Iron hand", which were developed in the last few years at Offenburg University, are presented. Even by today's standards, the first "Iron Hand"—as could be shown in the replicas—demonstrates sophisticated mechanics and well thought-out functionality and still offers inspiration and food for discussion when it comes to the question of an artificial prosthetic replacement for a hand. It is also outlined how some of the ideas of this mechanical passive prosthesis can be translated into a modern motorized active prosthetic hand by using simple, commercially available electronic components.

Keywords: Iron Hand; Götz von Berlichingen; 3D computer-aided design; finite element method; 3D multi-material polymer printing; replica; hand prosthesis; neuroprosthetics

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1. Introduction

The famous Franconian knight Gottfried (also called "Götz") von Berlichingen (1480–1562) was born into a time of upheaval during the transition from the late Middle Ages to modern times: Michelangelo (1475–1564), Copernicus (1473–1543), Luther (1483–1546), Paracelsus (1493–1541), and Vesalius (1514–1564) lived almost simultaneously. In 1514, slave shipments from Africa to America began, in 1519–1521 the Aztec empire was conquered, from 1518 to 1525 the plague raged throughout Europe, in 1519 Leonardo da Vinci died, and in 1533 Elizabeth I of England was born. Götz von Berlichingen bravely defended the ideals during the end of chivalry. Fighting numerous battles and engaged in numerous "feuds" with various other knights and even cities, one event is of particular importance for him: During the Landshut War of Succession (1504/05), he lost his right hand due to a cannon ball splinter injury in 1504 at the age of 24 years. The cannon fire came from his own countrymen by accident [1].

In his autobiography, which he dictated to a priest at the end of his life, Götz says, "Then a servant came to my mind, of whom I had heard from my father and old ... servants, called Köchli, who had had only one hand, and who, in the field, could have done just as well as any other man in the field. I prayed to God and thought to myself, even if I had twelve hands, and his grace and help would not be with me, it would be in vain. That is why I thought that if I had little spare by an iron hand, I wanted to be as efficient as any other frail man in the field" [2]. Götz already thought about replacing his hand artificially during his time in the sick bay and early on commissioned a gunsmith to build the first "Iron Hand". In this prosthesis, the artificial thumb and two finger blocks (index and middle finger, and ring finger and little finger, respectively) could be moved in their basic joints by a spring mechanism and released by a push button. Photographs of the first hand can be seen under the following permalinks of the Landesarchiv Baden-Württemberg, Abteilung Generallandesarchiv Karlsruhe:

- http://www.landesarchiv-bw.de/plink/?f=4-1081856-1 (hand closed);
- http://www.landesarchiv-bw.de/plink/?f=4-1081855-1 (hand open).

Some years later, presumably around 1530, a second "Iron Hand" was built. In this, the fingers could be moved passively in all joints. Photographs of the second hand can be seen under the following permalinks of the Landesarchiv Baden-Württemberg, Abteilung Generallandesarchiv Karlsruhe:

- http://www.landesarchiv-bw.de/plink/?f=4-1078548-1 (hand closed);
- http://www.landesarchiv-bw.de/plink/?f=4-1078549-1 (hand open).

Although the second prosthesis was more elaborate than the first prosthesis, it seems that the knight continued to use the first one much more often, as, opposed to the first, the second prosthesis has nearly no traces of usage. However, since only certain things could be held, the environment of Götz had to be adapted in such a way that dealing with the first "Iron Hand" was as simple as possible. In the museum at Jagsthausen, Germany, one can see some of these adapted instruments: his crossbow and his cutlery and travel set.

In 1815, the Basel copper engraver Christian von Mechel (1737–1817) illustrated and described the second "Iron Hand" and its artful mechanics in a detailed book, which contains two aquatint etchings in a scale of 1:1 [3]. Mechel, who was commissioned to draw the hand, dismantled it for this purpose, but was later unable to put it back together properly; one finger remained stiff and could not be repaired. In the early 1980s, Günter Quasigroch had the chance to inspect both hands and make some drawings from its inside, although he was not allowed to dissemble the hands [4,5]. Based on the work of Quasigroch, we reconstructed the first artificial hand by 3D computer-aided design (CAD) and printed it with a multi-material polymer printer. We also adapted some pieces of the mechanics, resulting in mainly three different variants of the hand's reconstruction.

In this piece, we would like to give a detailed overview on these reconstructions and show the reader further developments that translated the fascinating mechanical Götz prosthesis into a motorized artificial hand.

Please note: For further details on the mechanics, and the used software and hardware, please refer to the cited original research articles and theses. These are not part of this overview.

2. Reconstructions

2.1. The First 3D CAD Reconstruction

The first 3D CAD reconstruction [6] was based on data from Quasigroch, 1982 [4]. For static reasons, however, a few dimensional data points had to be changed, and since not all components of the riveted mechanical part of the Götz hand were visible to Quasigroch and thus measurable without destroying the hand, some assumptions were made for the reconstruction that resulted from the creation of the 3D CAD data (Figure 1). This 3D CAD reconstruction was then printed with a multi-material printer (Stratasys J750, Eden Prairie, MN, USA), which allows for the production of different polymer materials (including transparent, non-transparent, stiff, or elastic components) [7] (Figure 2).

(**a**) (**b**)

Figure 1. Initial 3D computer-aided design (CAD) reconstruction of the first "Iron Hand" of Götz von Berlichingen. (**a**) General view of the artificial prosthetic hand; (**b**) view after virtual removal of the chassis with insight into the mechanics.

Figure 2. Initial 3D-printed polymer replica of the first "Iron Hand" of Götz von Berlichingen.

In our investigations with the 3D-printed polymer replica, we found that simple actions for daily use, such as holding a wine glass, a mobile phone, a bicycle handlebar grip, a horse's reins, or some grapes, are possible without effort [8].

2.2. The Second 3D CAD Reconstruction with an Improved Thumb Lever Mechanism

During the use of the initial 3D reconstruction of the hand, it was observed that the thumb lever broke under greater stress. The increased forces mainly in the thumb lever could be confirmed by finite element method (FEM) analysis (see Figure 1 in [9] or under the link: https://doi.org/10.3390/prosthesis2030020). Therefore, the mechanism of the thumb lever was revised: The newly developed mechanism of the thumb joint, which causes the finger and thumb roller to rotate in opposite directions, was realized with two power levers. This improved the tension and the distribution of forces in the parts (maximum stress of about $2.5{\cdot}10^5\ \frac{N}{m^2}$ in the old mechanism versus $1.4{\cdot}10^5\ \frac{N}{m^2}$ (von Mises) in the new mechanism) [10]. The 3D-printed polymer replica can be seen in Figure 3.

(**a**) (**b**)

Figure 3. Second 3D-printed polymer replica of the first "Iron Hand" of Götz von Berlichingen with an improved thumb lever mechanism. (**a**) General view of the artificial prosthetic hand; (**b**) view after removal of the lateral chassis cover with insight into the new mechanics.

An animation of the second 3D CAD reconstruction of the first "Iron Hand" of Götz von Berlichingen with the improved thumb lever mechanism can be seen in Video S1. It shows the mechanics in great detail and is self-explanatory.

2.3. The Third 3D CAD Reconstruction with an Opening Mechanism by a Torsion Spring

In previous reconstructions, the resetting mechanism was not considered. In the original Götz hand, however, when the button is pressed, one can observe a clear rebound of the fingers to their original position. Quasigroch could not exactly fathom this mechanism, and so a spring mechanism was considered that could be well fitted into the existing mechanics. For this purpose, a torsion spring was selected for each finger block. Its strength was first calculated according to the principles of today's engineering art; then the springs were inserted into a slight 3D-CAD modification of the second variant of the replica described above. This (third) reconstruction was then printed out on a 3D printer; the inserted torsion springs can be seen in Figure 4 [11].

(**a**) (**b**)

Figure 4. Third 3D-printed polymer replica of the first "Iron Hand" of Götz von Berlichingen with an opening mechanism by a torsion spring. (**a**) In this photograph, the first finger block, the new thumb lever mechanism, and the lateral chassis cover are removed to see the torsion spring; (**b**) view of all components after disassembling the hand.

In Appendix A, some photographs of the third 3D-printed polymer replica are shown in everyday situations.

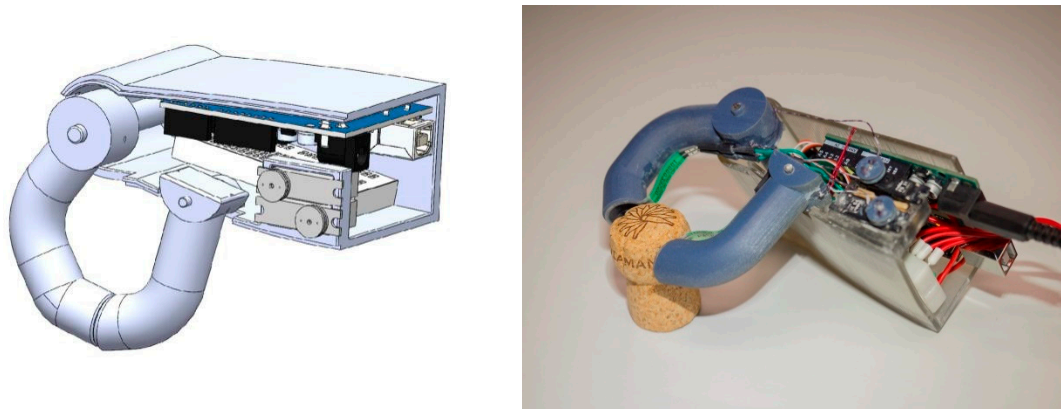
3. Further Developments

Subsequent to the “Iron Hands” of Götz, many other hand prostheses followed over the centuries. To name only a few: the hand from Eisfeld (16th century); the hand of the Turkish buccaneer Horuk Barbarossa (16th century); the hands of the famous physician Ambroise Paré (16th century); the Balbronian hand, which is quite similar to the second “Iron Hand” of Götz (16th century); the hand from Lamzweerde; the arm built by Carl Heinrich Klingert (end of the 18th century); the hands of Karoline Eichler (c. 1836), the artificial hands of Pfnor (c. 1840); the famous Sauerbruch hand prosthesis (first half of the 20th century); the Krukenberg arm (first half of the 20th century); the prosthesis of Edmund Wilms (Vaduz Hand, 1949), one of the first electromotor-driven prostheses; the pneumatic arm of Häfner (c. 1950); and the “Otto-Bock Elektro-Systemhand” (second half of the 20th century), one of the first myoelectrical prostheses [12].

Based on our above 3D polymer reconstructions of the first “Iron Hand” of Götz, we tried to translate some of the ideas of this mechanical *passive* prosthesis into a modern motorized active prosthetic hand. One example is shown in this overview, a sensorimotor, controller-controlled intelligent finger system. Another example with a modern motorized four-finger gripper system, whose fingers are ultimately based on the 3D CAD finger data of Götz, is presented in [13] (see this permalink: https://www.nature.com/articles/s41598-020-73250-6/figures/6).

Conversion of the Götz Hand to A Sensorimotor, Controller-Controlled Intelligent Finger System

In this work, an intelligent, controller-controlled sensorimotor finger system was reconstructed on the basis of the first “Iron Hand” of Götz. For this, two electronic, servo-motorized fingers, which mimicked the “tweezer grip” and automatically switched off at pre-set contact pressure, were built into the Götz hand chassis (Figure 5) [14].



(**a**) (**b**)

Figure 5. Conversion of the Götz hand to a sensorimotor, controller-controlled intelligent finger system. (**a**) 3D CAD reconstruction; (**b**) view after removal of the lateral chassis cover with insight into the electronics and servo motors. For further details on the hardware and software, please refer to [14].

This work showed that it is possible to develop an active hand with simple, commercially available electronic components that can perform convincing gripping functions even in a simple “tweezer grip”. Ultimately, only one on/off command was needed because the hand had programmable pressure sensors that, at a certain pressure, switched off the finger (i.e., the artificial thumb and/or the index finger) moved by a servo motor. The finger then remained in its position due to the locking gear of the servo motor. With the simple pressure sensors, this system worked as a closed-loop system, and we therefore called it the “sensorimotor, controller-controlled intelligent finger system”.

The functionality of this simple system, for example gripping a raw egg or a styrofoam ball between the two fingers, was amazing (Figure 6).

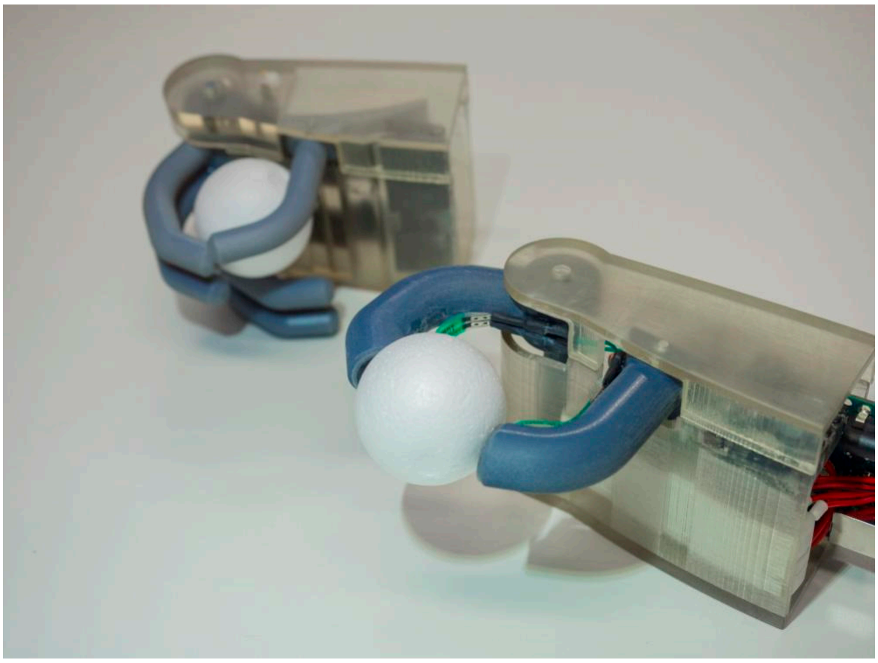


Figure 6. Comparison of the mechanical hand (reconstructed first "Iron Hand") with the electronic hand while holding a styrofoam ball. Here the active gripping system has a clear advantage over the passive mechanical hand, which only offers a holding function.

4. Conclusions

Historical prostheses are in no way primitive and, furthermore, ancient people already had the first intelligent "medical engineering" approaches [15–17].

In this review article, the first "Iron Hand" of Götz von Berlichingen and its reconstructions by Offenburg University are presented. For both historians and engineers, the fascination about Götz of the Iron Hand remains unabated to this day. Modern 3D printing of the replica reconstructions of Götz's artificial hand, as shown in the research work summarized in this overview, has suggested how the technologies of the past can inform current research as we move from history to the future [18].

Supplementary Materials: The following are available online at http://www.mdpi.com/2673-1592/2/4/27/s1, Video S1: Animation of the second 3D CAD reconstruction of the first "Iron Hand" of Götz von Berlichingen with an improved thumb lever mechanism.

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A

In Appendix A, some photographs of the third 3D-printed polymer replica are shown in everyday situations (Figures A1–A4).

Figure A1. Photograph of the third 3D-printed polymer replica in an everyday situation, example 1: handle of a barbecue.

Figure A2. Photograph of the third 3D-printed polymer replica in an everyday situation, example 2: handle of a garden hose.

Figure A3. Photograph of the third 3D-printed polymer replica in an everyday situation, example 3: branch of a peach tree.

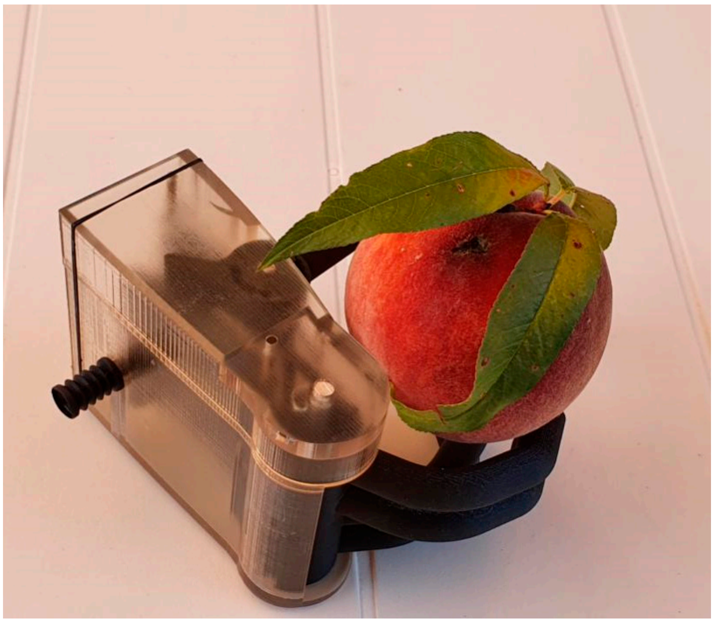

Figure A4. Photograph of the third 3D-printed polymer replica in an everyday situation, example 4: peach.

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Editorial

Christian von Mechel's Reconstructive Drawings of the Second "Iron Hand" of Franconian Knight Gottfried (Götz) von Berlichingen (1480–1562)

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In our recent review [1], we outlined the 3-dimensional (3D) computer-aided design (CAD) reconstructions of the first "Iron Hand" of German knight Götz von Berlichingen (1480–1562), a historical hand prosthesis of the Renaissance replacing the knight's right hand, which he, at the age of 24, had lost during the Landshut War of Succession due to a cannon ball splinter injury in 1504 [2,3].

In this piece, we focus on the second "Iron Hand". The hand prosthesis was built around 1530 by an unknown armorer, probably from the Franconian region, and still can be viewed in a glass showcase in the Castle Museum of Jagsthausen, Germany.

In 1815, the Basel-born engraver Christian von Mechel (1737–1817) illustrated and described the second "Iron Hand" and its elaborate mechanics in a short book of 10 pages that includes two detailed copper etchings (Figures 1 and 2) of the hand prosthesis at a scale of 1:1 (they are called Tabula I and Tabula II in the book) [4]. Mechel was given permission by the von Berlichingen family to dismantle the hand for this purpose.

In illustration 5 (with extended finger) and illustration 6 (with flexed finger) of Tabula II (see the two drawings on the lower left in Figure 2), the mechanism of the fingers is shown: after actuation of a locking lever in the chassis, a chain reaction is triggered in which an oblique hook jumps out of its opening by shooting up the proximal phalanx, thus releasing the locking of the medial phalanx; the medial phalanx then also jumps up and, by ejecting its oblique hook, in turn releases the locking of the distal phalanx (Figure 3).

In 1982, Günter Quasigroch was the second to inspect the original second "Iron Hand" [5], but this time he was not allowed to disassemble it. He noted that the overall mechanics were slightly coarser than those seen in Mechels' drawings. Quasigroch tested the functionality of this prosthesis in various everyday situations. The prosthesis did not seem very robust for heavy loads—the grip of the prosthesis was quite weak and loose, which probably did not allow the knight to wield a sword or a lance with this hand, since the mechanically very weak locking mechanism of the wrist did not allow this. In contrast, playing cards could be held effortlessly, and an attempt to write with a quill pen made from a swan feather was successful at first attempt.

Many designs and mechanisms of artificial hand prostheses still resemble those of the second "Iron Hand" of Götz von Berlichingen. Without the meticulous reconstruction of the copper engraver Christian von Mechel, this would probably not have been possible.

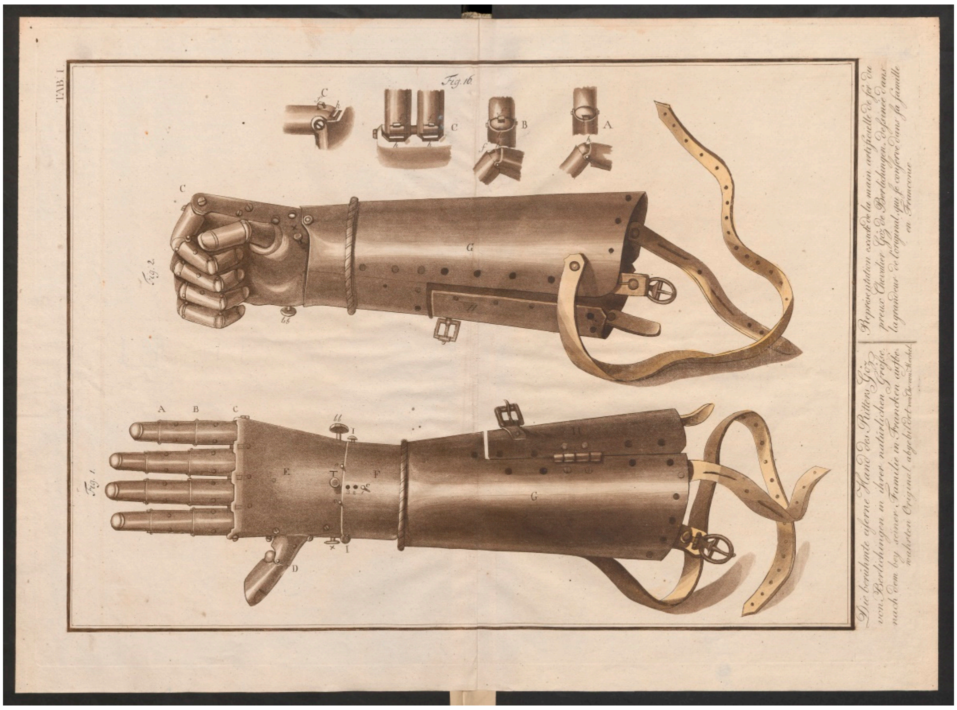

Figure 1. Götz von Berlichingen's second "Iron Hand", external hand and forend: two-piece, round, slightly conical bracer (forend) for attaching the prosthesis to the forearm. Hinged flap closed with two leather straps and buckles. Four individual fingers movable in three joints, thumb movable in only one joint (the base joint of the thumb is firmly connected to the body of the hand). Two buttons were used to return the thumb or the four remaining fingers to the normal position (open hand) by spring force.

Picture credit: Tabula I from Christian von Mechel's book, 1815 [3], entitled: "Die berühmte eiserne Hand des Ritters Göz von Berlichingen in ihrer natürlichen Größe, nach dem bey seiner Familie in Francken aufbewahrten Original abgebildet von Chr. von Mechel". ["The famous iron hand of the knight Götz von Berlichingen in its natural size, illustrated by Chr. von Mechel after the original kept with his family in Franconia"]. Picture credit: Mechel, Christian von: Die eiserne Hand des tapfern deutschen Ritters Götz von Berlichingen: wie selbige noch bei seiner Familie in Franken aufbewahrt wird, sowohl von Aussen als von Innen dargestellt: nebst der Erklärung ihres für jene Zeiten [. . .]. Berlin: gedruckt bei Georg Decker . . . , 1815. ETH-Bibliothek Zürich, Rar 2224, https://doi.org/10.3931/e-rara-14841 (accessed on 8 March 2021) (Public Domain Mark 1.0).

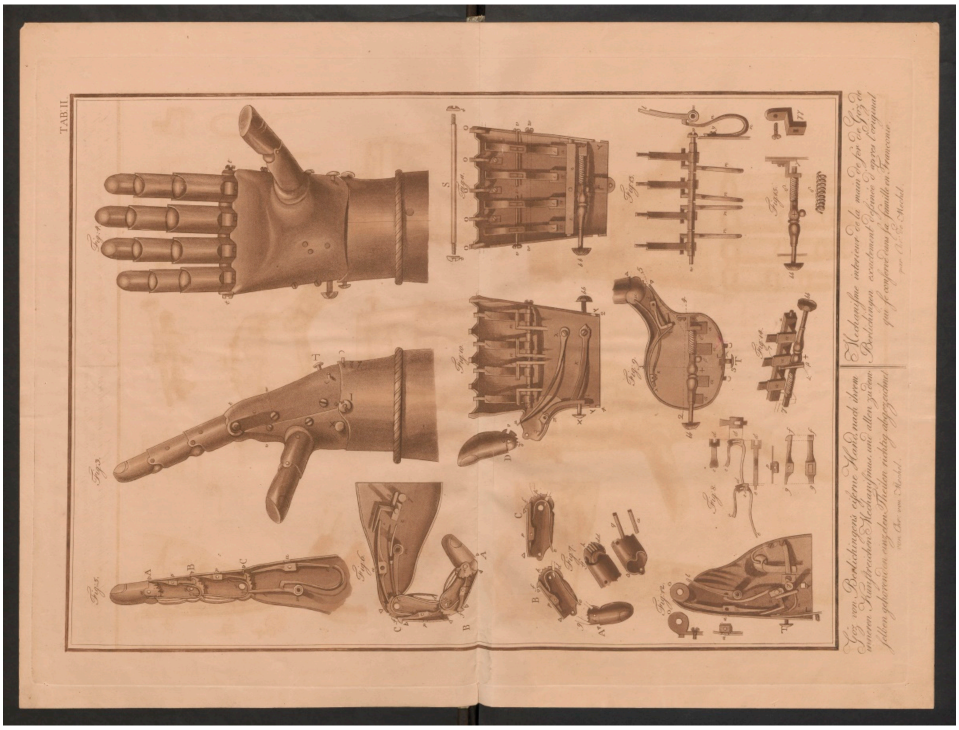

Figure 2. Götz von Berlichingen's second "Iron Hand"—overview of the mechanism of the fingers.

Picture credit: Tabula II from Christian von Mechel's book, 1815 [3], entitled: "Göz von Berlichingen's eiserne Hand, nach dem inneren kunstreichen Mechanismus, und allen zu demselben gehörenden Theilen richtig abgezeichnet von Chr. von Mechel". ["Götz von Berlichingen's iron hand, after the inner elaborate mechanism, and all parts belonging to the same correctly drawn by Chr. von Mechel"]. Picture credit: Mechel, Christian von: Die eiserne Hand des tapfern deutschen Ritters Götz von Berlichingen: wie selbige noch bei seiner Familie in Franken aufbewahrt wird, sowohl von Aussen als von Innen dargestellt: nebst der Erklärung ihres für jene Zeiten [. . .]. Berlin: gedruckt bei Georg Decker . . . , 1815. ETH-Bibliothek Zürich, Rar 2224, https://doi.org/10.3931/e-rara-14841 (accessed on 8 March 2021) (Public Domain Mark 1.0).

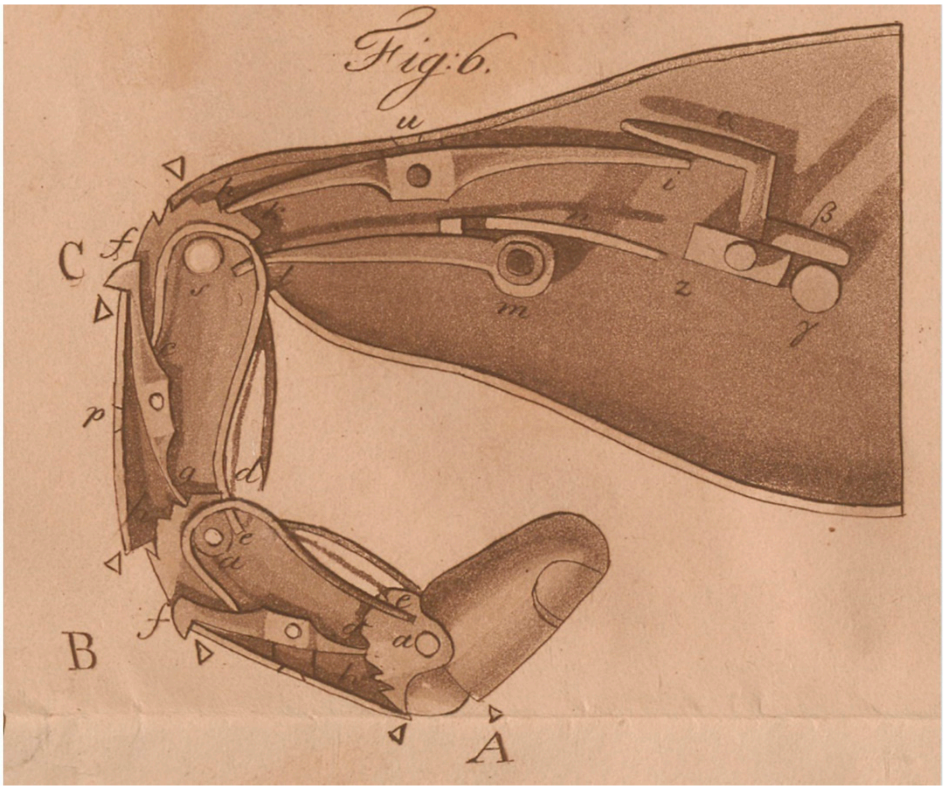

Figure 3. Götz von Berlichingen's second "Iron Hand"—detail of the finger mechanism: A–C: phalanges. A is hollow and closed on all sides. B and C are hollow but open on one side to accommodate articular vertebrae. *a*: Pins. The pins unite the phalanges. In addition, the two springs *e* are placed around them and the pin *S*. At *d*, the springs *e* are provided with an opening Δ into which the lower part of the spring of the abutting link engages. *f*, *g*: Locking lever. *p*: Hinge head. *h*: Teeth. *i*, *k*: Locking lever in hand body. In *i*, the locking lever is still connected to other levers. *u*: hinge head. *l*, *m*: tension hook. *n*: Spring. *α*, *β*: lever. *γ*: pusher. *z*: shaft.

Picture credit: Illustration 6 (entitled "Figure 6") enlarged from Tabula II (see Figure 2) of Christian von Mechel's book, 1815 [3], entitled: "Die berühmte eiserne Hand des Ritters Göz von Berlichingen in ihrer natürlichen Größe, nach dem bey seiner Familie in Francken aufbewahrten Original abgebildet von Chr. von Mechel". ["The famous iron hand of the knight Götz von Berlichingen in its natural size, illustrated by Chr. von Mechel after the original kept with his family in Franconia."]. Picture credit: Mechel, Christian von: Die eiserne Hand des tapfern deutschen Ritters Götz von Berlichingen: wie selbige noch bei seiner Familie in Franken aufbewahrt wird, sowohl von Aussen als von Innen dargestellt: nebst der Erklärung ihres für jene Zeiten [. . .]. Berlin: gedruckt bei Georg Decker . . . , 1815. ETH-Bibliothek Zürich, Rar 2224, https://doi.org/10.3931/e-rara-14841 (accessed on 8 March 2021) (Public Domain Mark 1.0).

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prosthesis

Editorial

Lessons Learnt from Götz of the Iron Hand

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1. Introduction

Recently, we reported the three-dimensional computer-aided design (3D-CAD) reconstruction of the first "Iron Hand" of the famous Franconian knight, Götz von Berlichingen (1480–1562), who lost his right hand by a cannon ball splinter injury in 1504 in the War of the Succession of Landshut [1–8]. In this early passive hand prosthesis, the artificial thumb and two finger blocks could be moved by a spring mechanism in their basic joints and released by a push button.

A second "Iron Hand" was developed many years later, in which the fingers could be passively moved in all joints. In most illustrations of Götz, the second "Iron Hand" is shown, although he is said to have mostly used the first hand because of its robustness and easy usability in everyday activities. We also studied the 1815 publication of the Basel copper engraver Christian von Mechel (1737–1817) who illustrated and described the second "Iron Hand" and its sophisticated mechanics, containing two useful aquatint etchings in a scale of 1:1 [9].

2. 3D-CAD Reconstruction of the Second "Iron Hand"

Today, we would like to share with you our new 3D-CAD reconstruction of the finger mechanics of the second "Iron Hand" based on the Mechel plot (Figure 1). In this reconstruction, you can observe how a chain reaction is triggered in the body of the artificial hand after the locking lever is actuated, in which the angled hook of the proximal phalanx jumps out of the opening, and thus releases the locking of the middle phalanx, which also jumps up and releases the locking of the distal phalanx when its angled hook jumps out.

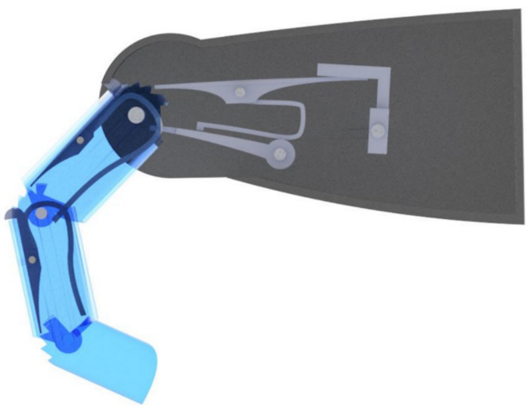

Figure 1. 3D-CAD reconstruction of the finger mechanics of the second "Iron Hand" of Franconian knight Götz von Berlichingen.

Thus, with one press on the locking lever button, the finger jumps from the preset flexion (Figure 2) to extend (Figure 3) in all joints.

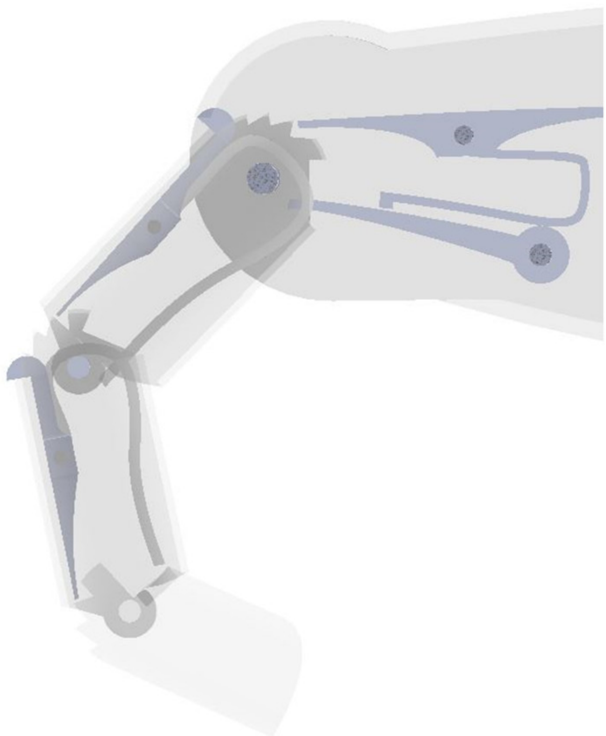

Figure 2. Detail of the 3D-CAD reconstruction of the finger mechanics; the hand is in the flexed position.

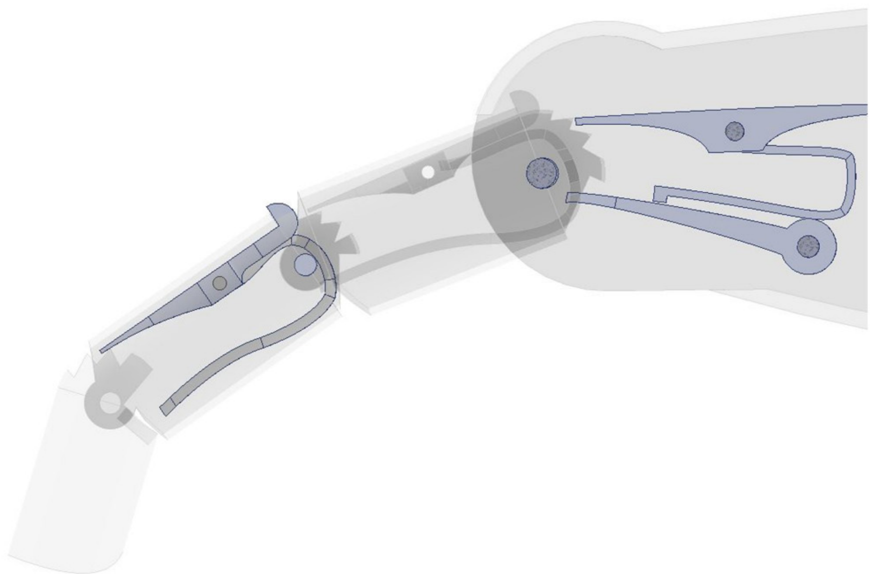

Figure 3. Detail of the 3D-CAD reconstruction of the finger mechanics; the hand is in the extended position.

3. Lessons Learnt

What can we learn from Götz?

1. This ancient hand prosthesis has very complicated mechanics;
2. The very detailed Mechel publication does not explain every detail of the hand and is not quite 1:1 in scale.
3. When printing the parts with a multi-material polymer printer, the levers and springs of the finger mechanism broke after only a few seconds, while the polymer replica of the first hand still functions perfectly after years of constant use. This indicates

that not all prosthetic hand designs are suitable for 3D polymer printing: Especially for such fragile parts, such as those inside the second prosthetic hand, a CAD-based computerized numerical control (CNC) fabrication from metal should be considered. In fact, the original hand in the museum of Jagsthausen, Germany, is also made of sheet alloy. Information on the stability, and thus the choice for the appropriate material, can be simulated in advance, e.g., with a dynamic finite element method (FEM) analysis.

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Conflicts of Interest: The author declares no conflict of interest.

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Article

3D Multi-Material Printing of an Anthropomorphic, Personalized Replacement Hand for Use in Neuroprosthetics Using 3D Scanning and Computer-Aided Design: First Proof-of-Technical-Concept Study

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Abstract: *Background*: This paper presents a novel approach for a hand prosthesis consisting of a flexible, anthropomorphic, 3D-printed replacement hand combined with a commercially available motorized orthosis that allows gripping. *Methods*: A 3D light scanner was used to produce a personalized replacement hand. The wrist of the replacement hand was printed of rigid material; the rest of the hand was printed of flexible material. A standard arm liner was used to enable the user's arm stump to be connected to the replacement hand. With computer-aided design, two different concepts were developed for the scanned hand model: In the first concept, the replacement hand was attached to the arm liner with a screw. The second concept involved attaching with a commercially available fastening system; furthermore, a skeleton was designed that was located within the flexible part of the replacement hand. *Results*: 3D-multi-material printing of the two different hands was unproblematic and inexpensive. The printed hands had approximately the weight of the real hand. When testing the replacement hands with the orthosis it was possible to prove a convincing everyday functionality. For example, it was possible to grip and lift a 1-L water bottle. In addition, a pen could be held, making writing possible. *Conclusions*: This first proof-of-concept study encourages further testing with users.

Keywords: amputee; anthropomorphic hand replacement; 3D multi-material printing; 3D light scanning; computer-aided design; neuroprosthetics; personalization

1. Introduction

Nowadays there are many different ways to design and manufacture a prosthesis for the upper limbs. The approaches to control a prosthesis can be roughly divided into two categories: non-invasive and invasive. A fascinating example for an invasive approach is the linking of intracortical recorded signals to the activation of the forearm muscles so that intact muscles can be controlled again [1]. On the other hand, there are some non-invasive concepts that use hybrid systems based on electroencephalography (EEG) and electrooculography (EOG) or electromyography (EMG) to control the prostheses [2,3]. Such concepts are impressive, but they are technically complex and associated with high costs and a high learning effort for the patient [4,5], so they are not suitable for every patient. Depending on the patient's life circumstances, there is a great desire for a functional, but as simple and inexpensive as possible prosthesis [4], which serves as a support in everyday life. For this reason, open communication between engineers and physicians is essential for the development of neuroprosthetics for the upper limb [6].

Some non-invasive concepts have already shown that even simple approaches can produce convincing results. These include, for example, body-powered prosthesis, which are cost-effective and allow the user to grip an object by moving a body part such as the shoulder [7]. In addition, 3D-printed prostheses have also been convincing with their cost-effective production for several years now. These include the Phoenix Hand from the e-NABLE organization, which is based on design data and controlled by wrist movement [8]. In other projects, 3D printing has proven to be a remarkable alternative to traditional methods such as casting. For example, a controller-controlled, sensorimotor finger system based on the reconstruction of the first "Iron Hand" of Götz von Berlichingen was produced by using a multi-material 3D printer [9].

This paper presents another approach to a hand prosthesis in which multi-material 3D printing plays a role. The hand prosthesis consists of a combination of a 3D-printed replacement hand and a commercially available electric orthosis, which is used e.g., by quadriplegics and allows gripping. Unlike the 3D printed prosthetics mentioned above, the 3D printed replacement hand is based on 3D scanning technology. If available, the healthy hand of a hand amputee is scanned and mirrored with a 3D structured light scanner, resulting in a 3D model of an anthropomorphic replacement hand that looks like the patient's own hand. To enable the replacement hand to move through the orthosis, a flexible material must be selected for the part of the hand above the wrist. The wrist, on the other hand, should be made of strong material to give the hand stability.

In the following, two concepts are presented that show how the combination of a replacement hand and orthosis works.

2. Results

2.1. Selection of the Material for the Replacement Hand

To select the material of the flexible part of the replacement hand, five individual fingers were printed with different materials. The main material is the flexible, rubber-like photopolymer Agilus30. By mixing Agilus30 with the rigid material VeroWhite, the properties of the material change. These properties were determined by bending the fingers manually (J.B.) and are shown in Table 1.

Table 1. Properties of the materials at increasingly high mixing ratios of Agilus30 with VeroWhite.

Finger	Shore-A-Value	Flexibility and Effort	Tearing	Strength
1	30	Full flexion with minimal force	no	soft, unnatural
2	40	Full flexion with average force	no	soft, unnatural
3	50	Full flexion with average force	no	medium, natural
4	60	Full flexion with above average force	no	rigid, natural
5	70	Full flexion with maximum force	yes	rigid, unnatural

The material chosen for the fully flexible part of the replacement hand was Finger 1, printed with pure Agilus30, although Finger 3 and Finger 4 feel most natural in terms of strength. When testing the fingers with the orthosis, Finger 1 could be flexed the most as the least force was required. In addition, no cracks were formed. The stronger flexion increases the number of objects that can be gripped with the prosthesis, which is why the criterion of functionality rather than strength prevailed in this case. The wrist was printed with the photopolymer VeroWhite. In total the replacement hand weighs 415 g. The results of the complete replacement hand are shown in Figure 1.

(**a**) (**b**)

Figure 1. 3D printing of the replacement hand. (**a**) Replacement hand from dorsal view; (**b**) replacement hand from palmar view.

In addition to the hand, which is made entirely of the flexible material above the wrist, another replacement hand was printed. This contains a simplified skeleton made of rigid material within the flexible part. Figure 2 shows the replacement hand with the constructed skeleton consisting of simplified phalanges and a block. The phalanges and the block are connected. The strong structure gives the replacement hand more stability as well as a more natural feeling and flexion of the fingers. In contrast to the replacement hand without a skeleton, the fingers can only be bent in places where the phalanges are not present. The replacement hand has a total weight of 419 g.

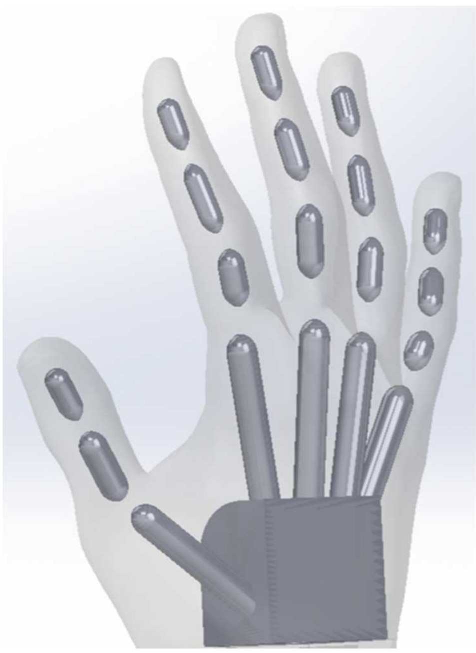


Figure 2. CAD model of the skeleton from simplified phalanges, which is placed inside the replacement hand.

2.2. Functionality Tests of the Replacement Hand

Both replacement hands were tested in combination with the orthosis to determine whether the prosthesis could be used in various everyday situations. Figure 3 shows the setup of the prosthesis. The orthosis can actuate the index and middle finger. The motor of the orthosis enables the simultaneous opening and closing of the index finger and middle finger. The thumb remains rigid. A Bluetooth remote control is used to control the orthosis by pressing two buttons.

Figure 3. Assembly of the first prosthesis: Combination of the replacement hand and the orthosis. The control unit of the orthosis is attached to the Armliner.

It is possible to grip and hold various objects with the prosthesis. The flexible material withstands several bending processes. One of the objects is a full 1-L bottle, which is gripped and held up. This is shown in Figure 4 and in Supplementary Materials Video S1. Other everyday situations such as opening a door or writing with a pen are also shown in Video S1. The tests have demonstrated that the hand prosthesis can be used to perform various grips that are useful for managing everyday life.

Figure 4. A full 1-L bottle is gripped and held up.

3. Discussion

This work has shown that it is possible to develop a functional and cost-effective hand prosthesis with a 3D-printed replacement hand combined with a commercially available motorized orthosis. It is fascinating how many different objects can be gripped and held. In addition, 3D scanning of a volunteer's hand made it possible to meet the optical requirements of an anthropomorphic and personalized replacement hand. The resemblance of the replacement hand to the real hand is very strong. It has five fingers and, regardless of the colors of the material, it looks like a real hand due to its natural shape and features such as fingernails and tendons. Also, the weight of the replacement hand is approximately the same as the weight of the real hand.

A further step towards a natural and aesthetic prosthesis will be the adaptation of the color of the replacement hand to the natural color of the skin of the hand amputee. Aesthetics plays an important role in the successful integration of the prosthesis into the patient's everyday life [10]. However, color matching may require intensive manual labor, which could increase the cost of the hand prosthesis. Furthermore, a wide variety of particles such as dust adhere to the surface of the Agilus30 material. A possible coating of the replacement hand could prevent this. A biocompatible coating of silicone is conceivable in order to be able to use the replacement hand completely harmlessly for medical use. Another possibility would be to print the replacement hand directly with a silicone that is biocompatible.

Up to now, a complete closure of the fingers by the chosen orthosis could not be achieved. This is due to the positioning of the thumb. When closing the fingers, the fingers are pulled towards the thumb by a stable cord. If the thumb is too far away from the index finger, the index finger and middle finger are bent sideways and do not close completely. For this reason, the correct position of the fingers should be ensured during the 3D scan. Generally, the scanning process is a challenge, since the hand must ideally be held in the resting position for up to two minutes. Even small movements of the fingers can lead to faulty images. This is why a 3D scan plan should be developed to standardize the scanning process.

Currently, a remote control is needed to control the prosthesis. This requires that the user of the prosthesis have a healthy hand with which he can operate the two buttons on the remote control. A novel approach to electrodeless visual control of the orthosis with augmented reality glasses can counteract this [11,12], which is worth testing.

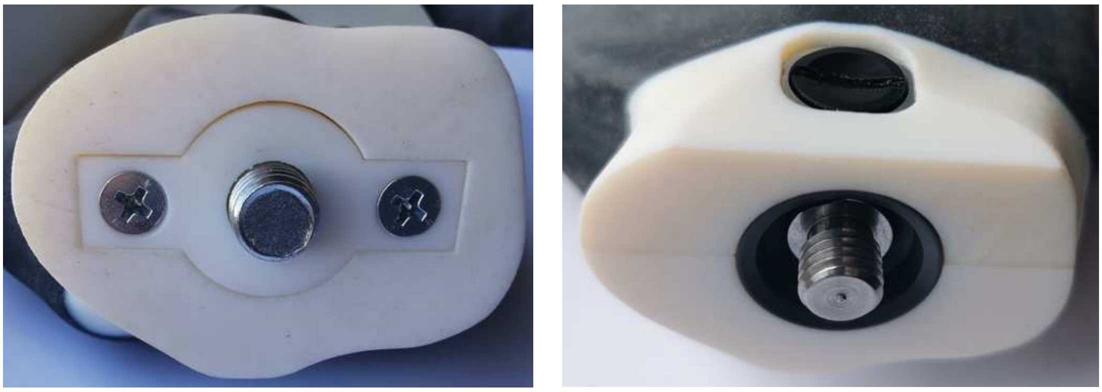
The impressive results of this proof-of-technical-concept study encourage further clinical studies with users.

4. Materials and Methods

The 3D scan of a volunteer's hand (S.H.) was performed with a structured light 3D scanner (Artec Eva, Artec3D, Luxembourg). The resulting 3D model was exported as a mesh file in STL format. The resulting mesh body was then converted into a solid body using a CAD program (SolidWorks 2019, Dassault Systèmes, Vélizy-Villacoublay, France). SolidWorks was also used to separate the solid body in the area of the wrist into two parts, allowing different materials to be assigned to the two parts. A fastening system was integrated into the wrist part (Figure 5) of each replacement hand. Additionally, the skeleton was inserted into the flexible part of the second replacement hand.

The two replacement hands were printed using a multi-material 3D printer (Stratasys J750, Eden Prairie, MN, USA), which allows to print an object with several materials in one step. This approach allows to manufacture the model without additional work steps, such as the construction of casting molds. In addition, the registration of the skeleton structure in the hand can be accurately handled within the CAD program. The 3D printer utilizes the polyjet printing technique, which uses a liquid photopolymer as base material.

To select the material of the part of the hand above the wrist, individual fingers were printed with different blends of the photopolymers Agilus30 and VeroWhite. Agilus30 has similar properties to rubber in terms of appearance, haptics and function. It has a Shore-A-value of 30, making the material very flexible. In addition, compared to other rubber-like photopolymers, it has a higher tensile strength, a higher tear resistance and a higher elongation at break [13]. These properties are significant because the flexible part of the replacement hand must be able to withstand multiple bending and flexing processes without tearing. The photopolymer VeroWhite becomes rigid after curing [14]. By mixing the two materials with different mixing ratios, new materials with new properties are created. The more VeroWhite is added to Agilus30, the higher the Shore-A-value. As a result, the material becomes stronger, but also increasingly brittle. The printed fingers were bent manually [15]. It was observed how much force was required to achieve a full flexion of the fingers and whether tears were formed in the material during flexion. A secondary criterion was the strength of the material, although this was neglected in retrospect, since the complete flexion of the fingers was more crucial. In the end, after several manual bending processes of the fingers, the pure Agilus30 was chosen for the flexible part of the hand. The wrist part was printed with pure VeroWhite.



(a) **(b)**

Figure 5. Replacement hands with the assembled fastening systems. (**a**) Fastening system with a hexagon head screw; (**b**) fastening system with a locking system.

The skeleton was also printed with VeroWhite. Originally, the skeleton was supposed to consist of mechanical joints and phalanges. In order to ensure that the joints can move, the areas around the joints had to be free of material. With the polyjet printing process, no overhangs can be built, so free areas are filled with a gel-like supporting material. Since the support material is inside the hand and completely surrounded by model material, it cannot be removed. Therefore, it should be used as a cartilage replacement. Nevertheless, the flexible outer material around the joints is too thin, which is why it is torn the first time the finger is bent with the orthosis. For this reason, the variant of a skeleton without joints was designed and used, in which no tears occurred despite repeated bending.

In addition, a fastening system was developed and designed for each replacement hand on the wrist, so that the replacement hands can each be mounted on a commercially available arm liner. The main part of the fastening system of the replacement hand without the integrated skeleton is an M10 threaded screw with a hexagon head, which fits into the M10 threaded hole in the arm liner. Therefore, the head of the screw must be installed in the wrist of the replacement hand. For this purpose, a counterpart has been constructed which fits exactly on the head of the screw and is screwed to the wrist. Figure 5a shows the assembled fastening system. For the fastening system of the replacement hand with the integrated skeleton, a locking system (5W055 Shuttle-Lock, Wagner Polymertechnik GmbH, Silkerode, Germany) was used. It consists of a plastic housing with two notches, a release button and a locking pin, which in turn consists of an insert thread and an M10 threaded screw. By pressing the release button, the locking system allows the replacement hand to be attached to the liner and to be removed again. The housing of the locking system was installed in the wrist, so that the release button can be pressed from the dorsal view. The fastening system is shown in

Figure 5b. Some more detailed photographs of the 3D-printed wrist of the replacement hand including the fastening systems are shown in Appendix A.

Supplementary Materials: The following are available online at http://www.mdpi.com/2673-1592/2/4/34/s1, Video S1: Functionality tests of the replacement hand in everyday situations.

Author Contributions: Conceptualization, all; methodology, all; validation, all; formal analysis, J.B.; investigation, J.B.; writing—original draft preparation, J.B.; writing—review and editing, S.H. and A.O.; visualization, J.B.; supervision, S.H. and A.O.; project administration, A.O. All authors have read and agreed to the published version of the manuscript.

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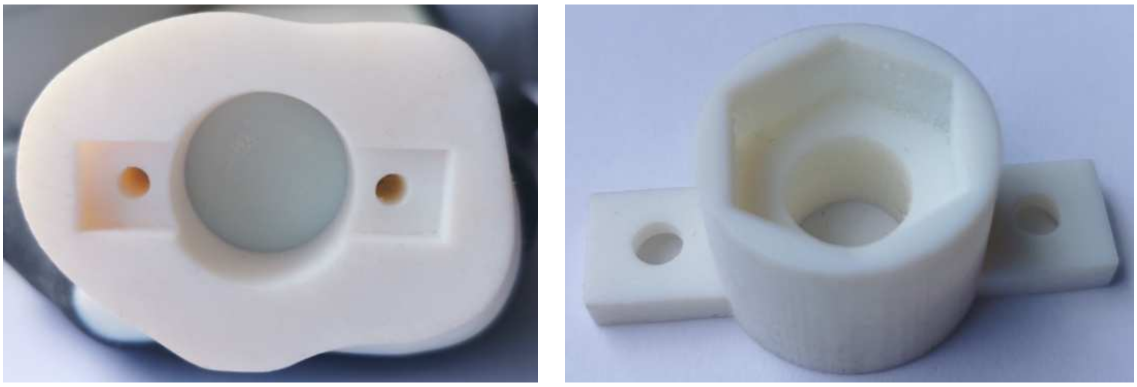
Appendix A

In Appendix A, some more detailed photographs of the 3D-printed wrist of the replacement hand including the fastening systems are shown (Figures A1 and A2).



(**a**) (**b**)

Figure A1. Fastening system with a hexagon head screw. (**a**) Counterpart for the hexagon head screw; (**b**) wrist of the replacement hand with a recess for the hexagon head screw and the counterpart.

(**a**) (**b**)

Figure A2. *Cont.*

(**c**)

Figure A2. Fastening system with a locking system. (**a**) First part of the wrist with a recess for the locking system; (**b**) the locking system is installed in the wrist; (**c**) second part of the wrist.

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Article

Conceptualization of a Sensory Feedback System in an Anthropomorphic Replacement Hand

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Abstract: (1) Background: This paper presents a conceptual design for an anthropomorphic replacement hand made of silicone that integrates a sensory feedback system. In combination with a motorized orthosis, it allows performing movements and registering information on the flexion and the pressure of the fingers. (2) Methods: To create the replacement hand, a three-dimensional (3D) scanner was used to scan the hand of the test person. With computer-aided design (CAD), a mold was created from the hand, then 3D-printed. Bending and force sensors were attached to the mold before silicone casting to implement the sensory feedback system. To achieve a functional and anthropomorphic appearance of the replacement hand, a material analysis was carried out. In two different test series, the properties of the used silicones were analyzed regarding their mechanical properties and the manufacturing process. (3) Results: Individual fingers and an entire hand with integrated sensors were realized, which demonstrated in several tests that sensory feedback in such an anthropomorphic replacement hand can be realized. Nevertheless, the choice of silicone material remains an open challenge, as there is a trade-off between the hardness of the material and the maximum mechanical force of the orthosis. (4) Conclusion: Apart from manufacturing-related issues, it is possible to cost-effectively create a personalized, anthropomorphic replacement hand, including sensory feedback, by using 3D scanning and 3D printing techniques.

Keywords: amputee; anthropomorphic hand replacement; 3D-light scanning; silicone; mold; neuroprosthetics

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1. Introduction

There are more and more active prostheses available that allow sophisticated grip types with varying grip strengths. However, the implementation of an appropriate feedback system is an open challenge concerning manufacturing-related topics, such as nanotechnologies, as well as medical aspects, such as invasive and non-invasive approaches [1–3]. Vibrotactile stimulation is often used to provide feedback to the patient in non-invasive techniques, as in [4–6]. In [7,8] or [9], visual techniques were used, whereby in the former two works, LEDs provide visual feedback concerning the gripping process, and in the latter work, the changed body scheme is simulated and visualized. Many other studies have shown that feedback can support the grasping process with a prosthesis during training or everyday use [10–12].

More recently, three-dimensional (3D) scanning and 3D printing have also been used in prosthesis construction, as it offers special possibilities for personalization [13,14].

Therefore, we present an approach to a personalized replacement hand with sensory feedback that can be realized with commercially available parts [15]. The signals acquired by the sensors can subsequently be processed by visual or vibrotactile feedback.

This paper is based on the prework of Baron et al., which dealt with 3D printing of an anthropomorphic and personalized replacement hand [16]:

In this project, the test person's hand was scanned with a 3D scanner and processed in a computer-aided design (CAD) program. Then, the hand was 3D printed from the rubber material Agilus30. The printed replacement hand had to be flexible for usage in combination with a motorized orthosis (NeoMano by Neofect) for paralyzed patients, in which the thumb is rigid and only index and middle finger are motorized. However, the study showed that the selected material was too stiff to be flexed by the orthosis. Due to the limited availability of flexible 3D printable materials, other personalized replacement hand manufacturing methods were evaluated [17].

Additionally, the study confirmed that the manufacturing process of such a 3D printed hand was time-consuming and expensive due to the costs for the 3D printable rubber material. In light of the aforementioned prestudy, the following paper presents the possibility of obtaining a personalized replacement hand using a silicone casting method. In this process, a mold is constructed from the 3D scanned model of the hand. Next, the mold is 3D printed, and a two-component room temperature vulcanizing silicone is filled in. After curing is completed, the personalized replica of the hand can be demolded. Since the replacement hand is intended to be used with a motorized orthosis as a cost-effective and personalized prosthesis, several silicone materials with different mechanical properties are tested. The selection of materials focuses on ensuring that the prosthetic hand feels natural in terms of a body-like rigidity of the hand, rather than a skin-like feeling. The second objective of this work is to integrate a sensory feedback system into the replacement hand to provide information about grip strength, consistency of the object grabbed, and the degree of grasp. This information could be displayed in a further step, for example, color-coded or by text messages through an augmented reality system as shown in [18,19] or through vibrotactile feedback. In order to cast the sensors in the proper position, thin spacers are integrated into the mold to attach bending and pressure sensors and hold them at the intended position during the casting process. As the replacement hand is designed to be used with the aforementioned orthosis, two pressure sensors and one bending sensor are integrated into the index and middle finger. The bending sensor measures the degree of flexion of the entire finger. Two force sensors are added, one at the fingertip and one at the proximal end of the finger. These are the two points that are mainly affected by the object during the gripping process. Both sensors are placed directly under the skin surface.

2. Results

2.1. Finger Test Series for Sensor Attachment

An initial test series determined how the sensors could be attached to the mold and how the sensors would behave after curing. In Table 1 the test set is listed to reference the manufactured fingers in Figure 1. These are examined in more detail for their softness, sensor attachment options, and sensory behavior. The test results lead to suggestions for improvement, which are adopted for the final replacement hand. With a Shore hardness of 25 ShA, the material of the fingers does not feel any softer than the Agilus30 replacement hand in Baron et al. [16], although the latter has a Shore hardness of 30 ShA. It should be mentioned that fingers with integrated sensors become stiffer, demonstrated by a reference finger without sensors. Even if the sensors themselves are more flexible than a whole finger, combining sensor and finger results in a stiffer model, as the silicone core may not deform undisturbed as before. If the orthosis flexes these test fingers, a complete flexion of the fingers is not possible yet, as the elasticity is not sufficient. Therefore, silicone material with a much lower Shore hardness is needed. Upon analyzing the sensory activity during the influence of force, it was found that all sensors in the corresponding fingers were functional.

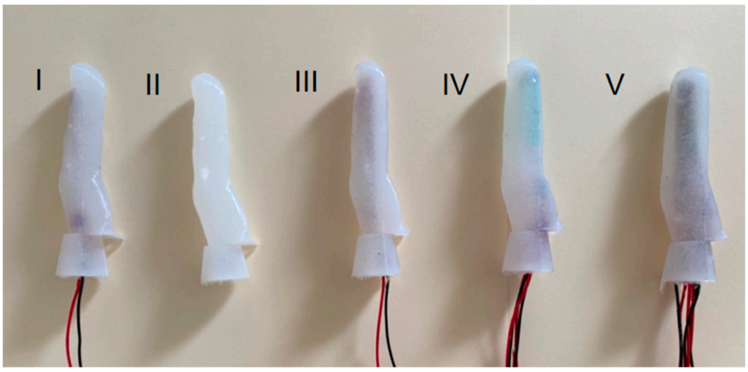

Figure 1. Overview of silicone fingers for sensor mounting. I Bending sensor mounted on wire, II Reference finger without sensors, III Bending sensor, IV Force sensor, V Force and bending sensors.

2.2. *Test Series for Combining Silicones with Different Shore Hardnesses during Casting*

Since the material of the fingers to include sensors had to be much softer than the rest of the hand to be flexed by the orthosis, a second test series was driven to investigate the behavior of the silicone during vulcanization and to address the question of whether it is possible to add a second silicone so that both materials connect but do not mix.

In Figure 2, it can be seen at the first finger (1) that the materials of this finger have been mixed. The hardness of both silicones is approximately averaged. In the remaining fingers (2–5), the fingers become more transparent from about the halfway point. These parts are marked in red. The firmness of the fingers is substantially softer in the upper half, while the other half is harder. The upper half is comparable to the sensorless reference fingers of the previous test series. The lower half is comparable to a sensorless finger made of 10 ShA silicone.

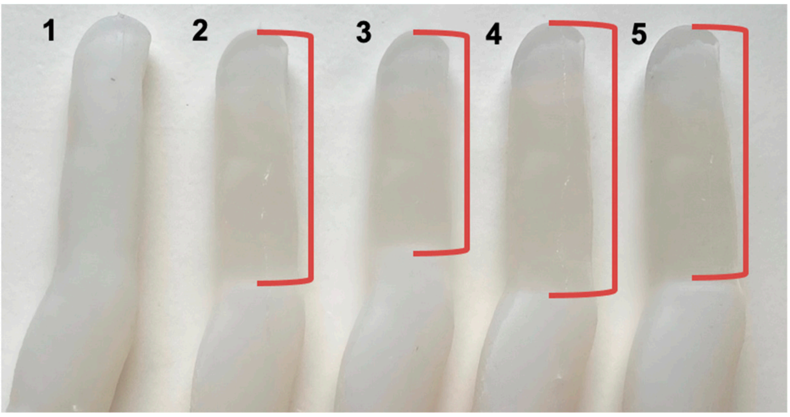

Figure 2. Overview of the silicone fingers for material analysis. Different waiting periods between the filling process of the softer and the harder material: (1) 0 minutes, (2) 10 minutes, (3) 10 minutes, (4) 20 minutes, (5) 20 minutes.

Both parts were adhered permanently to each other, which confirmed that the cross-linking during the curing process of two silicone materials is possible. As a result, it can be stated that the optimum time to fill in the second material is after 10 to 20 min.

2.3. *Replacement Hands*

From the three hands with various silicones with shore hardnesses of 25 ShA, 10 ShA, and 00 ShA the hand with Shore hardness 10 feels anthropomorphic but cannot be bent by the orthosis. In contrast, the replacement hand with Shore hardness 00 ShA proved functional in combination with the orthosis. However, it does not feel anthropomorphic because the material is too floppy and soft. Consequently, a combination of both silicones was needed: softer for the index and middle fingers and harder for the rest of the hand, respectively. The hand in Figure 3 shows the finished hand after molding; Figure 4 presents the replacement hand in combination with the orthosis.

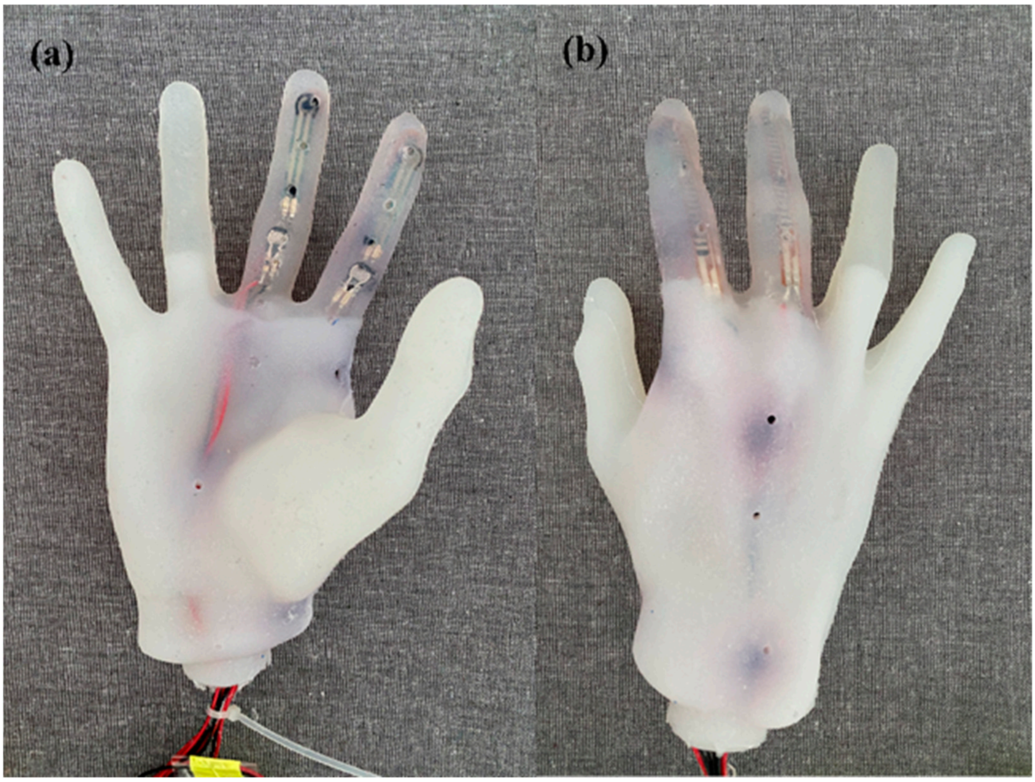

Figure 3. Hand using the silicone material with shore hardness 00 ShA for middle and index finger and shore hardness 25 ShA for the rest of the hand. (**a**) View from below; (**b**) View from above.

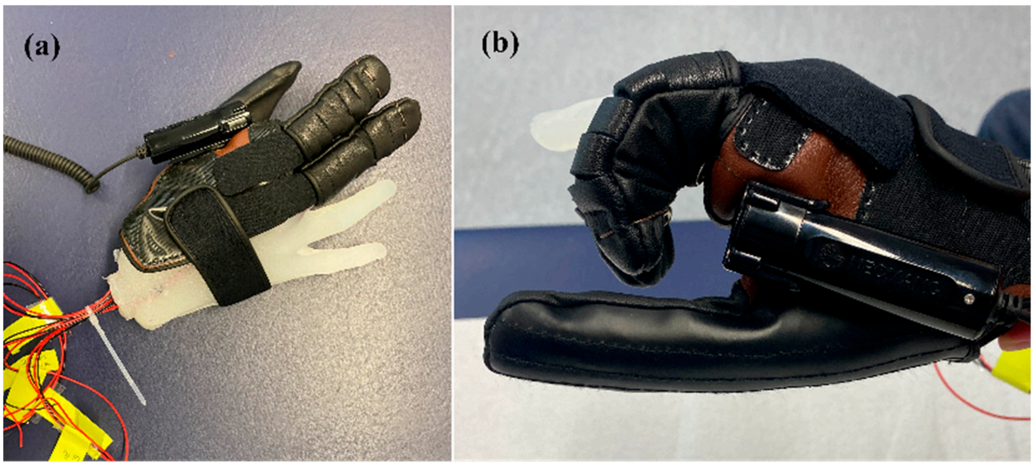

Figure 4. (**a**) Combination of the replacement hand with the orthosis. (**b**) Fingers flexed by the orthosis.

2.4. Evaluating the Sensory Feedback

The aim of testing the sensory feedback system was to prove that the molded sensors can measure meaningful measurements during the grasping process and also to evaluate the quality of the signals. In the individual analysis on the bending and force sensor, the flexion sensor revealed linear and the force sensor logistic behavior, as indicated in Figure 5a,b, respectively. Both sensors showed reproducible results.

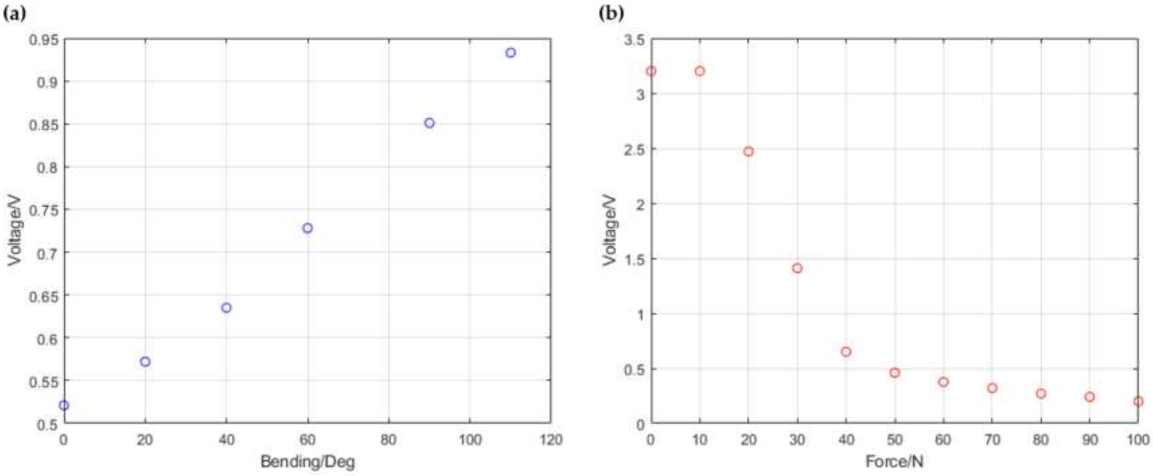

Figure 5. (**a**) Measured voltage values during flexion of the finger. (**b**) Voltage values of force senor under increasing force.

The measurements of sensory feedback during the grasping process of different objects provide repeatable and consistent results. The force sensor registers a different signal when gripping objects of similar shape and dimensions but different firmness, i.e., the bottle and the paper roll, which both had the same diameter (refer Figure 6a,b,d,e). However, while grabbing the paper roll, the force sensor measures only a signal during the gripping process (see Figure 6c,f). Despite squeezing it slightly, the paper roll does not have enough stiffness to generate sufficient force to the sensor in a stationary state. This shows that due to the strength of the leather of the glove, no exact haptic resolution is feasible. Nevertheless, with increasing force application, a linear progression of the sensory value can be observed. In a static state, i.e., while holding the object, the signal of the force sensor is noisier than the signal of the bending sensor, but for most applications, the measured noise level is acceptable (see Figure 6).

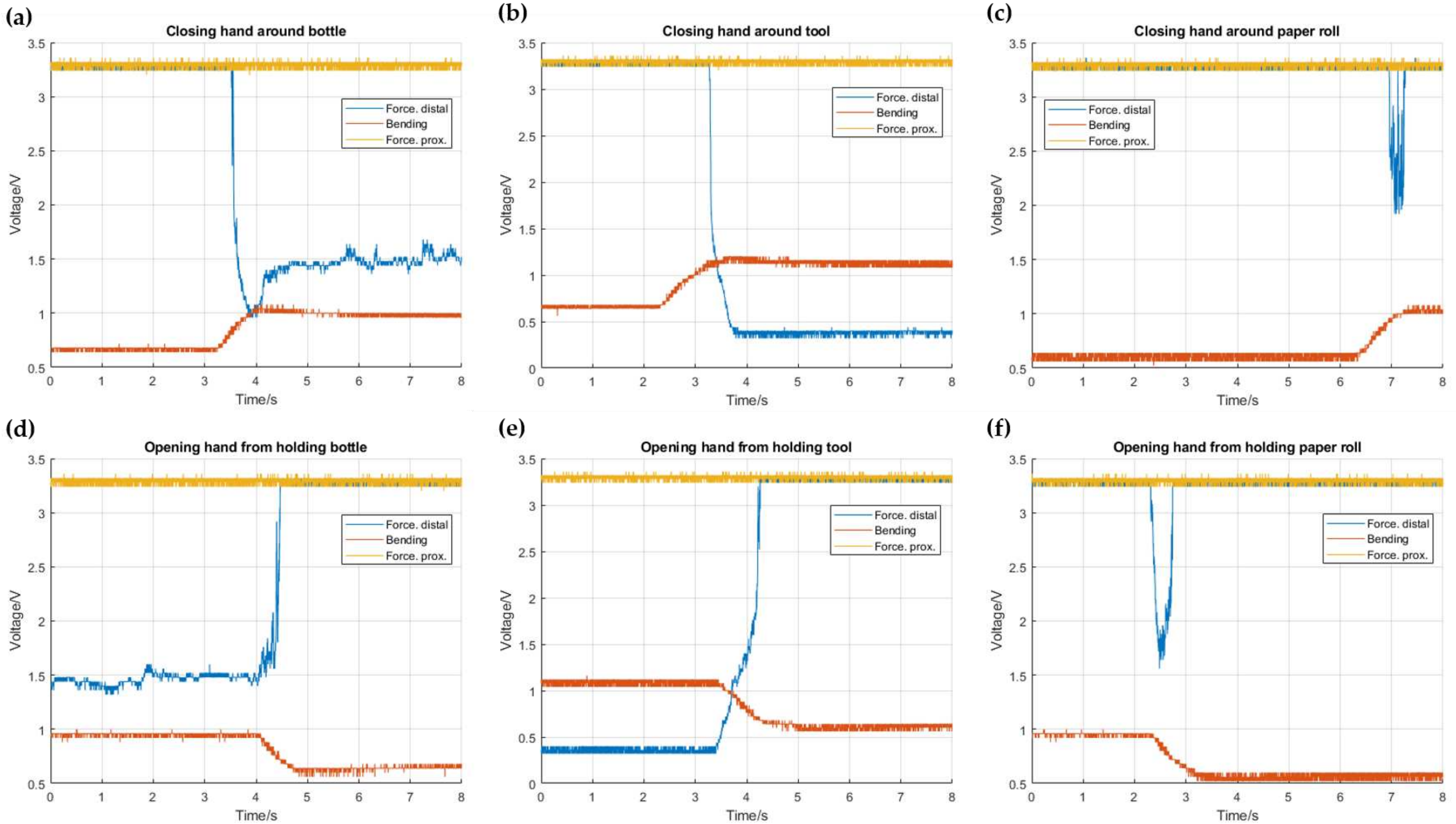

Figure 6. Measured sensor signals of grabbing different objects. (**a**) Closing hand around a small but solid bottle. (**b**) Closing hand around a 10 mm Allen key. (**c**) Closing hand around paper roll with same diameter as the bottle. (**d**) Signal of opening the hand from holding the bottle. (**e**) Signal of opening the hand from holding the Allen key. (**f**) Signal of opening the hand from holding the paper roll.

3. Discussion

In this work, a personalized prosthesis hand has been created by silicone casting using a 3D-printed mold. As the costs for manufacturing the personalized 3D-printed mold are low, compared to a personalized mold, manufactured by conservative techniques, this approach can be considered cost-effective.

In addition, possible solutions to integrate sensory feedback into such a prosthesis are shown.

It emerged that two different silicone materials were required for the replacement hand, as even the 10 ShA silicone in combination with its sensors became too stiff to be driven by the motor of the orthosis.

Unfortunately, the 00 ShA silicone was so soft that the sensors were not sufficiently fixed, leaving their position in the finger during flexion. It was observed that sensor parts might abrade each other, leading to the corresponding sensors' failure. To overcome this challenge and even simplify the manufacturing process, it may be beneficial to use a single material with larger Shore hardness and strengthen the mechanism in the orthosis. Additionally, it is essential to note that the soldering joints of the sensors suffer from mechanical stress (see Figure 7a). These rigid parts of the sensor are placed optimally outside the movable parts of the finger or in the core of the finger, where the surrounding material gives more stability.

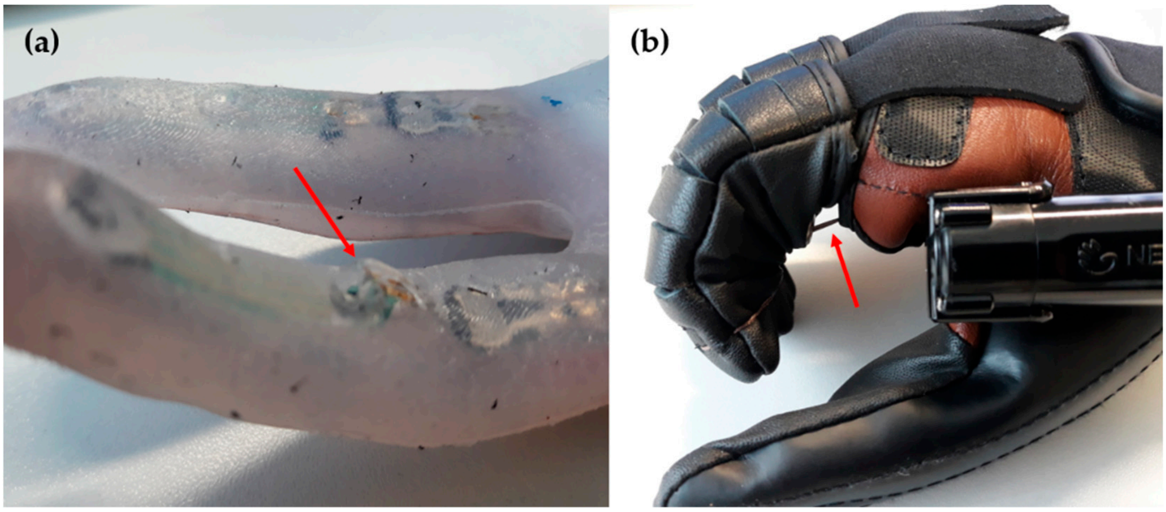

Figure 7. Sensory feedback issues: (**a**) Soldering joints potentially pushed out as the material was too soft. (**b**) Cord was spanned during the bending process and prevented the object from touching the force sensor.

Another issue occurred, concerning the second force sensor at the proximal end of the finger. It turned out that the cord that flexes the finger during the grasping process is spanned between the object and the sensor in a way that the sensors are not affected by the object (see Figure 7b). Therefore, no signal is measured by this sensor, as can be seen in Figure 6. A solution for this might be a new routing of the cord inside the glove.

Regarding the sensory feedback, it could be demonstrated that the degree of hand closure and the grip strength could be measured. As a result, this replacement hand allows the patient to get some sort of haptic feeling apart from the current motor function. Further research should clarify the extent to which this sensory feedback system can support the patient in learning to handle the prosthesis or also in everyday usage. For this purpose, further research should point out to which form and presentation the measured signals are optimally converted to be most helpful to the patient.

To improve the visual appearance of the replacement hand, the silicone material can be given any color by adding a color pigmentation. In doing so, matching the color of the replacement hand to the patient's skin color can promote greater patient acceptance.

4. Materials and Methods

4.1. Test Series to Evaluate Sensor Attachment

In this test series, different mounting options for sensor attachment were defined and tested. How the embedded sensors will behave in the cured silicone was tested. In addition, the optimal diameter of the spacers was tested for. In Table 1 the configurations of four test fingers and one reference finger are listed. The central concept for mounting the sensors in the mold was adding some bars, i.e., spacers, to which the sensors are attached. These cylindrical bars protrude from the mold, whereas the sensors are attached using glue that can be detached after casting. In Finger I, another concept for fixing the sensors in the mold was tested. Here, the bending sensor is attached to a wire with reversible glue led out through the funnel opening. The Fingers III to V include force and bending sensors as also a combination of both sensor types, respectively.

Table 1. Concept of sensor mounting. Finger II does not have any sensors and serves as a reference.

Finger	Measurement	Sensor Mounting
I	Flexion	Wire
II	-	-
III	Flexion	Bar
IV	Pressure	Bar
V	Pressure and Flexion	Bar

SILIXON 25 material was used for this test series. The casting was conducted according to the following steps: After the sensors and cables had been securely fastened, both mold components were screwed together. Then one half of the silicone base and one-half of the catalyst were mixed until a homogeneous mass was formed. The silicone was then carefully poured into the mold. The vulcanization process took about 4 h at a temperature of approx. 25 °C. After five hours, both silicone halves were released from each other, and the finished hand was carefully removed from the mold. Thereby the spacers detached from the sensors.

4.2. Test Series for Combining Silicones with Different Shore Hardnesses during Casting

As the index and middle fingers needed lower stiffness for usage in combination with the orthosis and in regard to the test series results for material analysis, the replacement hand was realized with two different silicones. Two silicones with different Shore hardnesses can be mixed, resulting in the average of both initial hardnesses. Therefore the first material (e.g., the softer one) had to cure to a certain degree before the second material (e.g., the stiffer one) could be filled in.

To investigate the possibility of realizing a silicone hand consisting of different silicone materials, an additional test series was performed. During the test, it was investigated after which period the second casting of a more rigid silicone material can occur. The focus was on ensuring that the two materials did not mix but still adhered to each other. Table 2 shows an overview of the castings for each test finger. After filling in the first material, a specific time was waited and the other silicone was poured in subsequently.

Table 2. Composition of the silicone fingers for material analysis with the different Shore hardnesses.

Finger	Shore-A-Value of the First Part	Time in Minutes until the Second Material Is Filled in	Shore-A-Value of the Second Part
1	00	0	10
2	00	10	10
3	00	10	10
4	00	20	10
5	00	20	10

4.3. Manufacturing Process of a Silicone Replacement Hand, Including Pressure and Bending Sensors

First, the hand was scanned using a structured-light 3D scanner to create a personalized hand, shown in Figure 8a. Subsequently, the scanned mesh body was converted to a solid so that the hand could be processed in the Autodesk Inventor CAD program, which is shown in (b). Thereafter followed the construction of the mold. The mounting options for the sensors were designed into the mold of the hand and the mold was 3D printed with a Prusa i3 MK3S FDM-based 3D-printer which can print polyethylene terephthalate glycol (PETG) material (c). PETG material is easy to process, has a low risk for warping, and has high strength. The robustness is important because the mold must be fastened with screws to be tight.

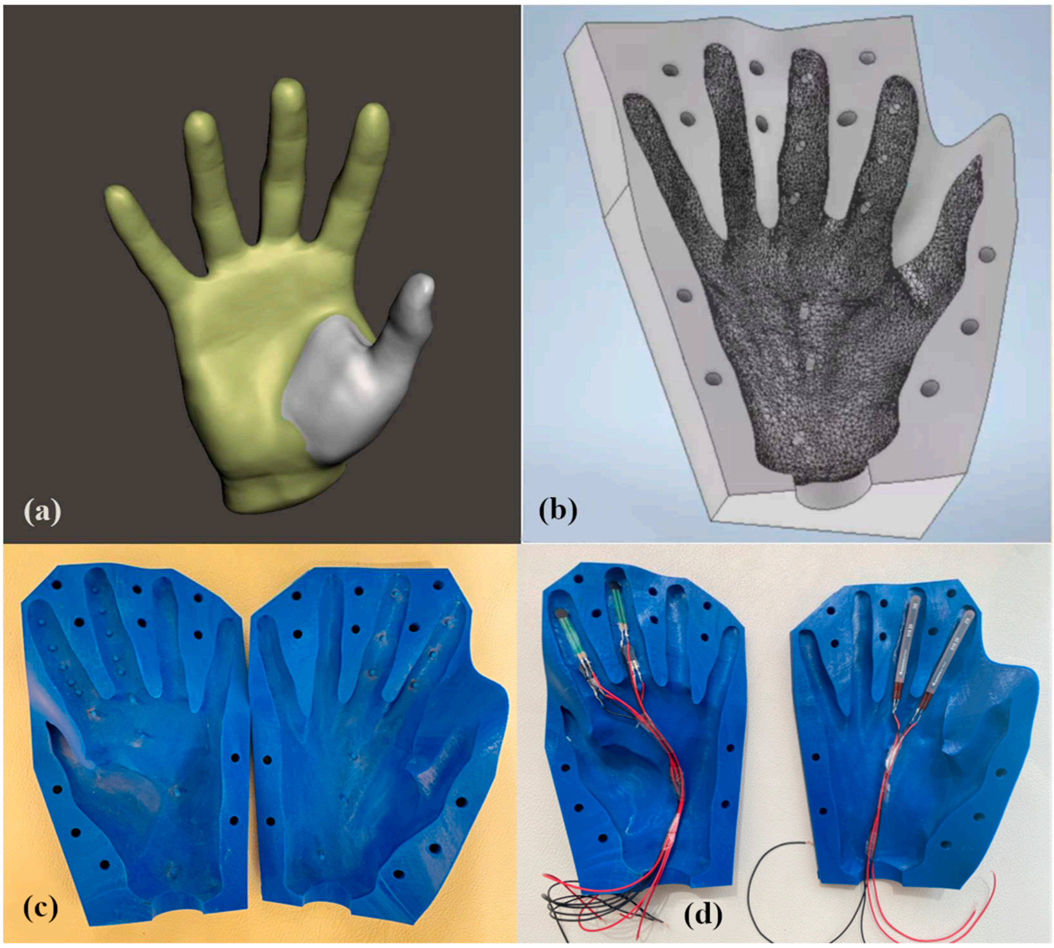

Figure 8. Conceptualization. (**a**) 3D-scanned hand; (**b**) Casting mold component created in CAD; (**c**) 3D-printed mold components; (**d**) Mold components with attached sensors.

In the next step, the attachment of the force and bending sensors into the fingers of both components was done (d). Finally, both parts of the mold were put together and liquid silicone was poured in.

An additional process step was introduced to manufacture the replacement hand using two different silicones. Flexible plastic tubes were inserted into the lower mold and fixed using glue. These were used for directed injection of the softer silicone material into the index and middle fingers. After filling the softer silicone into both fingers, the tubes were carefully pulled out and, after ten minutes, the harder silicone material was poured into the remaining areas of the hand. During the test, the 00 ShA silicone material was used for the soft fingers and the 25 ShA silicone material for the more rigid part of the hand.

4.4. Evaluating Sensory Feedback System

Both sensor types, i.e., force and bending sensors, used force-sensing resistor technology (Force sensors from Interlink and Flex sensor from SpectraSymbol). Thus, the resistance of these sensors varied with applied force or flexion, respectively. The positioning of the sensors is made as shown in Figure 9. A simple voltage divider circuit was implemented, to measure the variations in the resistance of the sensors. The resistance of all three sensors of one finger was measured simultaneously using a multichannel oscilloscope.

In a first test, the encapsulated sensors were tested individually. For this purpose, two fingers, both consisting of SILIXON 25 material, were mounted on a manual rotation table (see Figure 10a,b) and a floating bar to evaluate the behavior of the bending and force sensor, respectively. The rotary table was adjusted in steps of 20 degrees and the resistance variation measured the bending behavior via a voltage dividing circuit. To evaluate the force sensor, a vertical force was applied to the finger lying on its back and was measured by a force gauge, as shown in Figure 11.

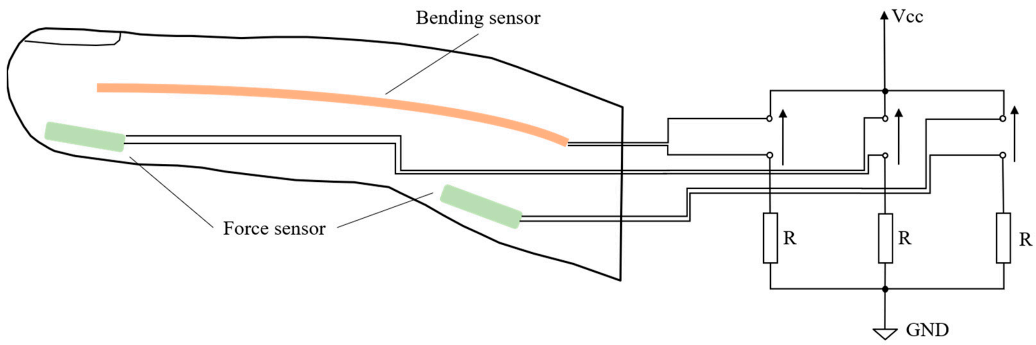

Figure 9. Positioning of bending and force sensors. On the right, the circuit diagram for measuring the sensor signals is shown.

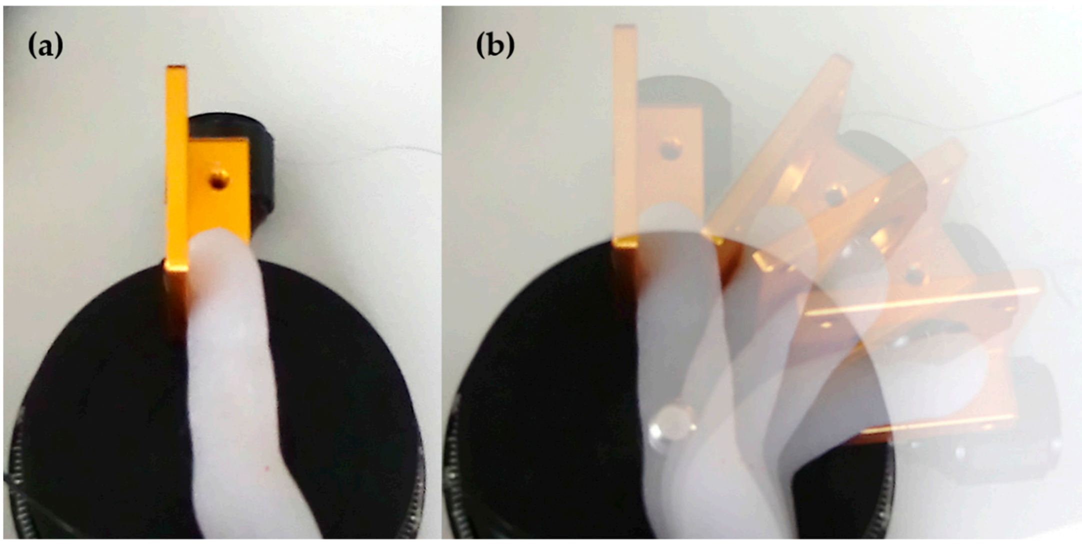

Figure 10. Setup to evaluate the bending sensor. (**a**) Finger mounted on the rotary table. (**b**) The rotary table is adjusted in steps of 20 degrees.

4.5. Evaluating Sensory Feedback System Using Neofect Orthosis

In a further test, the replacement hand was tested with the orthosis from Neofect. This orthosis is pulled over the paralyzed or restricted hand as a glove. The thumb of the orthosis is rigid and acts as an abutment while the index and middle finger are motorized and able to enclose an object. The orthosis is controlled by an external, Bluetooth-enabled controller that is held in the patient's healthy hand. The orthosis can hold up to 2 kg, therefore a full bottle of water can be held without effort.

During the trial, three different objects were grabbed by the replacement hand integrated into the orthosis. First, a small hard bottle was caught, shown in Figure 12a. Second, a thin and hard tool was used to measure the signals caused by the more significant degree of hand closure (Figure 12b). Last, a paper roll with the same diameter as the bottle in the first test was used to measure the capability of the force sensors to distinguish between objects of different consistency (Figure 12c). In Video S1, see Supplementary Materials, grabbing a small bottle and a paper roll during measurements are shown.

Figure 11. Measurement setup to analyze the force sensor. Force is applied to the proximal sensor using a flexible (purple) band.

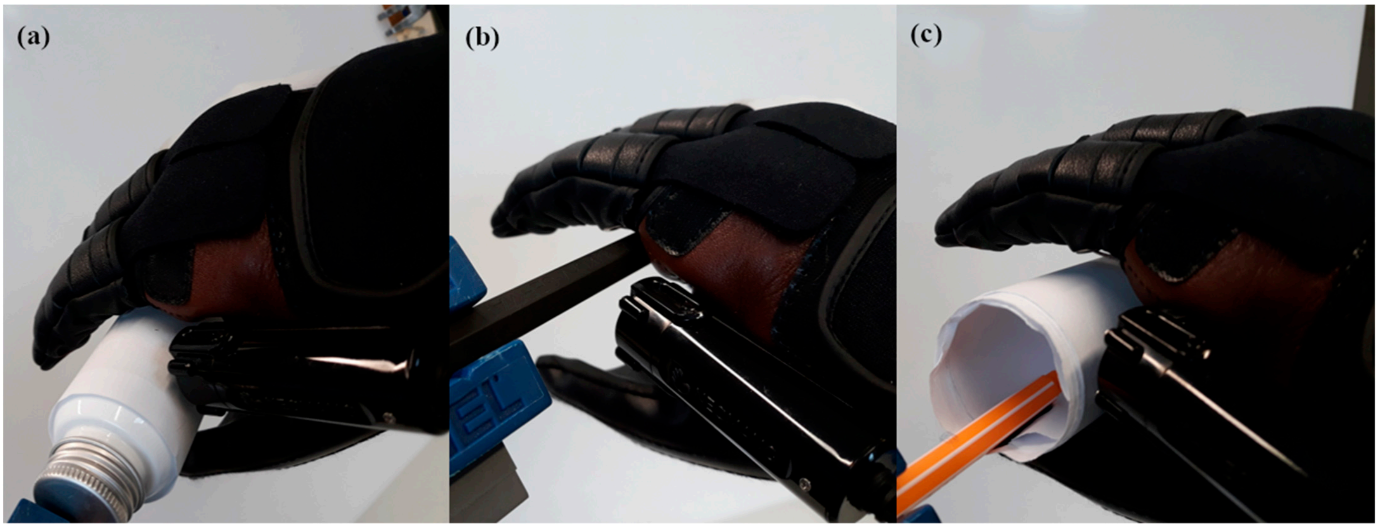

Figure 12. (**a**) Grabbing a small bottle; (**b**) Gapping a thin steel tool; (**c**) Grabbing a multilayered paper roll.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/prosthesis3040037/s1, Video S1: Grabbing small bottle and multilayered paper roll during measurements.

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This book comprises the 3D-CAD reconstructions of the two historical Iron Hands of knight Götz von Berlichingen up to new derived concepts of anthropomorphic, personalized replacement hands for use in neuroprosthetics.

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