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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

Andreas Otte

Laboratory of NeuroScience, Division of Medical Engineering, Department of Electrical Engineering, Medical Engineering and Computer Science, Offenburg University, Badstr. 24, D-77652 Offenburg, Germany; andreas.otte@hs-offenburg.de

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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

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.

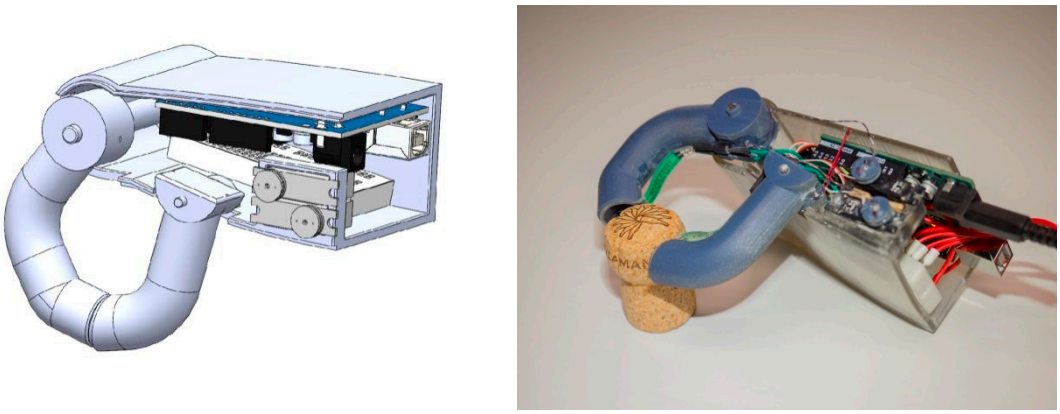
3. Further Developments

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).

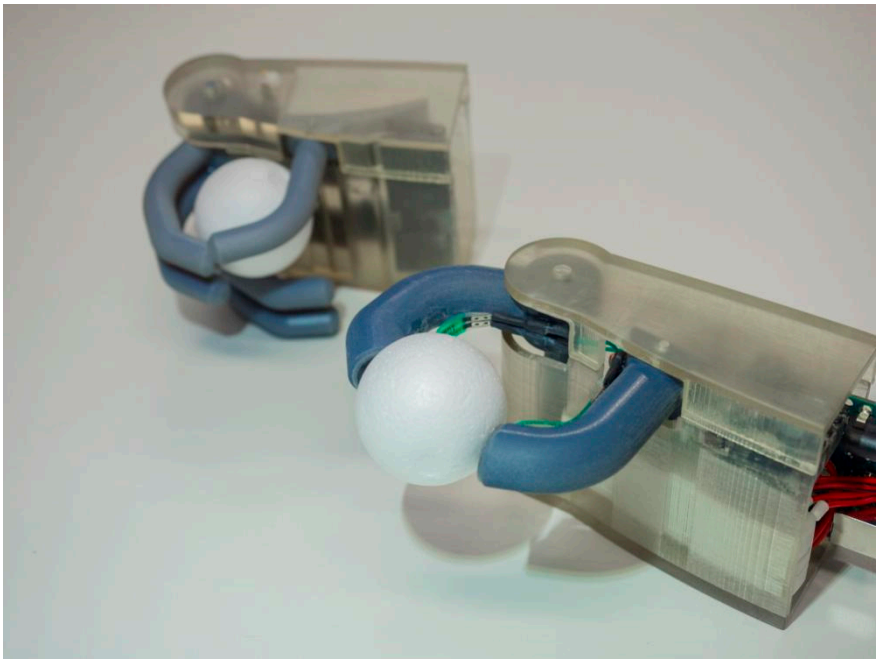


Figure 6. Comparison of the mechanical hand (reconstructed first "Iron Hand") with the electronic hand while holding a styrofoam ball. Here the active gripping system has a clear advantage over the passive mechanical hand, which only offers a holding function.

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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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.

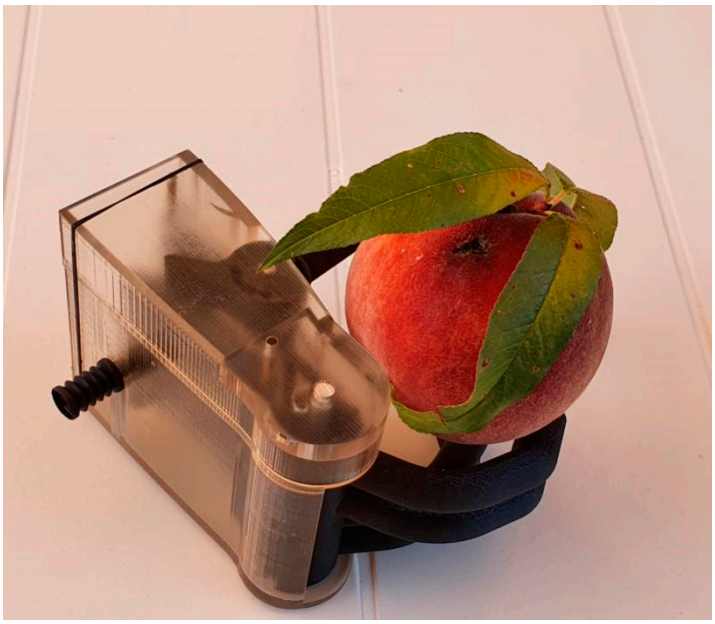

Figure A4. Photograph of the third 3D-printed polymer replica in an everyday situation, example 4: peach.

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