1
Introduction to Prehension Technology

Human labour has always been associated with the acquisition of specific skills, methods, and tools making the work and its environment easier and more effective. Increasing competition from industrial robots for tasks normally carried out by human hands has led to the need for more effective handling equipment, especially prehension tools (more commonly called “grippers”). However, industrial robots are not simply a substitute for people. Their relevance is more often in applications beyond the normal ability (physical or temporal) of conventional manpower. Examples include, dirty, hazardous and repetitive work. Just as human hands are the organs of human manipulation, so are robot grippers usually the only parts in direct contact with the workpiece. For this reason they deserve special attention – to which this book is dedicated.

1.1
Grippers for Mechanization and Automation

Grippers are active links between the handling equipment and the workpiece or in a more general sense between the grasping organ (normally the gripper fingers) and the object to be acquired. Their functions depend on specific applications and include:
- Temporary maintenance of a definite position and orientation of the workpiece relative to the gripper and the handling equipment.
- Retaining of static (weight), dynamic (motion, acceleration or deceleration) or process specific forces and moments.
- Determination and change of position and orientation of the object relative to the handling equipment by means of wrist axes.
- Specific technical operations performed with, or in conjunction with, the gripper.

Grippers are not only required for use with industrial robots: they are a universal component in automation. Grippers operate with:
- Industrial robots (handling and manipulation of objects).
- Hard automation (assembling, microassembling, machining, and packaging).
- NC machines (tool change) and special purpose machines.
- Hand-guided manipulators (remote prehension, medical, aerospace, nautical).
- Workpiece turret devices in manufacturing technology.

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- Rope and chain lifting tools (load-carrying equipment).
- Service robots (prehension tools potentially similar to prosthetic hands).

In robotics technology grippers belong to the functional units having the greatest variety of designs. This is due to the fact that, although the robot is a flexible machine, the gripper performs a much more specific task. Nevertheless, these tasks are not limited to prehension alone which is why the more generic term "end-effector" is often used.

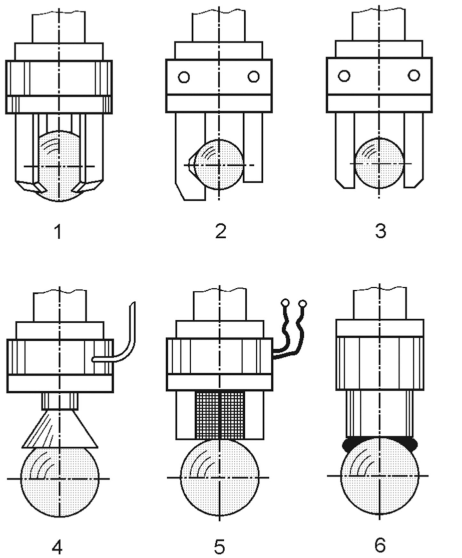
The great number of different requirements, diverse workpieces and the desire for well adapted and reliable systems will continue to stimulate further developments in future gripper design. Many experts consider the capabilities of the gripper as an essential factor for the economic effectiveness of automatic assembly systems. Experience indicates that in the future it will only be possible to respond to practical demands if flexible designs for assembly equipment are available. Consequently, grippers must become ever more flexible. Assembly relates not only to prehension and manipulation of objects but also to pressing, fitting and joining operations. Many grippers are employed for the loading of manufacturing lines, in packaging and storage as well as the handling of objects in laboratory test and inspection systems.

More recently, miniaturized grippers have been developed in order to handle delicate components in microtechnology. This has gone hand in hand with the emergence of many novel prehension methods. The number of grippers used in nonindustrial areas, e.g. in civil engineering, space research, handicraft, medical and pharaceutical engineering is steadily increasing. Hand-guided (teleoperation) or automatic manipulators are used in these areas primarily as handling machines. In addition to conventional grippers, for which the gripper jaws are shaped according to the workpiece profile, there exist numerous application specific grippers. This explains why an overwhelming proportion of corresponding patent literature is devoted to prehension concepts of unconventional design. In general, end-effectors are not normally within the delivery remit of robot manufacturers. Depending on the specific requirements, they are selected as accessories from tooling manufacturers or specially designed for the given purpose.

1.2 Definitions and Conceptual Basics

Grasping organs or tools constitute the end of the kinematic chain in the joint system of an industrial robot and facilitate interaction with the work environment. Although universal grippers with wide clamping ranges can be used for diverse object shapes, in many cases they must be adapted to the specific workpiece shape.

> **Grippers** are subsystems of handling mechanisms which provide temporary contact with the object to be grasped. They ensure the position and orientation when carrying and mating the object to the handling equipment. Prehension is achieved by force producing and form matching elements. The term "gripper" is also used in cases where no actual grasping, but rather holding of the object as e.g. in vacuum suction where the retention force can act on a point, line or surface.



1 pure enclosing without clamping
2 partial form fit combined with clamping force
3 pure force closure
4 holding with vacuum air (pneumatic force closure)
5 retention using magnetic field (force field)
6 retention using adhesive media

Fig. 1.1: Possibilities for prehension of a spherical object

Three of the most usual forms (impactive, astrictive and contigutive) of object prehension are depicted in six different examples in Figure 1.1.

One should differentiate between grasping (prehension) and holding (retention) forces. While the grasping force is applied at the initial point of prehension (during the grasping process), the holding force maintains the grip thereafter (until object release). In the many cases the retention force may be weaker than the prehension force. The grasping force is determined by the energy required for the mechanical motion leading to a static prehension force. The functional chain *drive → kinematics → holding system* is given, however, only for mechanical grippers. Astrictive vacuum suction grippers require no such kinematics [1-1].

There are some characteristic terms that are often used in prehension technology. Grippers consist mostly of several modules and components. In the following, the most essential terms used will be explained considering as an example a mechanical gripper such as the one shown in Figure 1.2.

A short glossary of further important terms used in gripper technology is briefly explained below.

Astrictive gripper: A binding force produced by a field is astrictive. This field may take the form of air movement (vacuum suction), magnetism or electrostatic charge displacement.

Basic jaw (*universal jaw*): The part of an impactive gripper subjected to movement. An integral part of the gripper mechanics, the basic jaw is not usually replaceable. However, the basic jaws may be fitted with additional fingers in accordance with specific requirements.

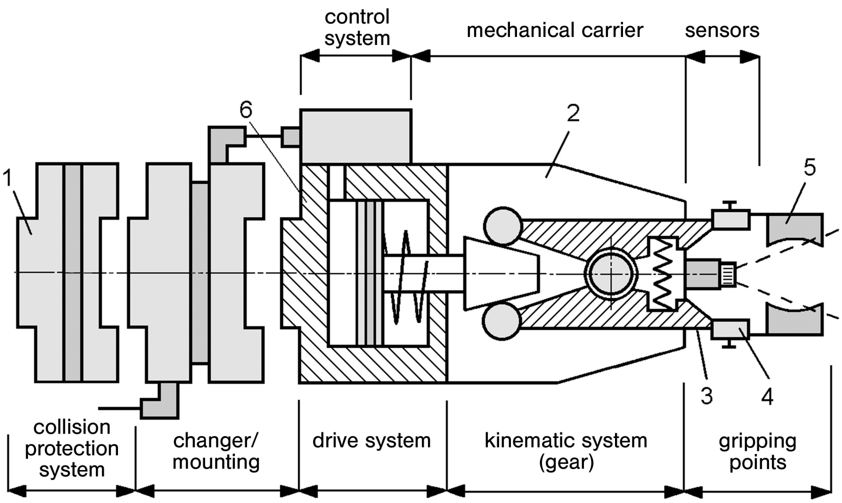
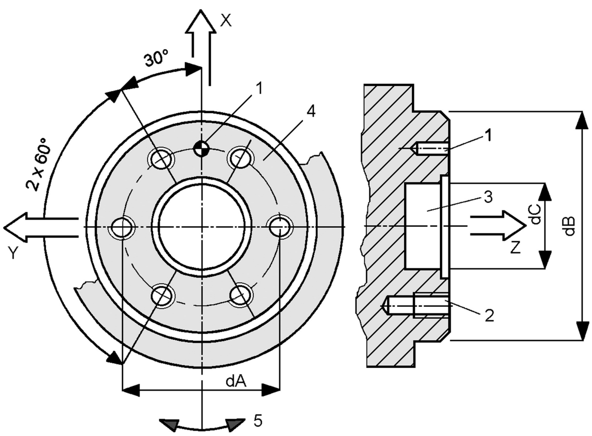


Fig. 1.2: Subsystems of a mechanical gripper
1 remote centre compliance, 2 carrier, 3 gripper finger, 4 basic jaw, 5 extended jaw, 6 flange

Basic unit: Basic module containing all gripper components which is equipped for connecting (flange, hole pattern) the gripper to the manipulator. The connecting capability implies a mechanical, power, and information interface. Figure 1.3 shows a flange design in accordance with DIN ISO 9409. This German industrial standard and its subsequent amendments contain design requirements concerning the different overall size, pitch circle diameter, centring cylinder dimensions, number of threaded holes and respective thread pitch as well as some position tolerances. The flange can also be drilled to allow feeding of power and control cables.

Chemoadhesion: Contigutive prehension force by means of chemical effects. Usually in the form of an adhesive (permatack or single use).



1 mating hole for locating pin
2 threaded securing hole
3 centring cylinder
4 flange body
5 flange rotation

dA pitch circle diameter
dB centring cylinder diameter
dC inner cylinder diameter

Fig. 1.3: Example of flange design and mounting in accordance with German standard DIN ISO 9409

Contigutive gripper: Contigutive means touching. Grippers whose surface must make direct contact with the objects surface in order to produce prehension are termed contigutive. Examples include chemical and thermal adhesion.

Control system: In most of the cases a relatively simple control component for analysing or pre-processing sensor information for regulation and/or automatic adjustment of prehension forces.

Dextrous hand: Anthropoidal artificial hand (rarely for industrial use), which is equipped with three or more jointed fingers and may be capable of sophisticated, programmed or remote controlled operations.

Double grippers: Two grippers mounted on the same substrate, intended for the temporal and functional prehension of two objects independently.

Drive system: A component assembly which transforms the applied (electrical, pneumatic, hydraulic) energy into rotary or translational motion in a given kinematic system.

Dual grippers: Two grippers mounted on the same substrate, intended for the simultaneously prehension of two objects.

Electroadhesion: Prehension force by means of an electrostatic field.

End effector (*end-of-arm tooling*): Generic term for all functional units involved in direct interaction of the robot system with the environment or with a given object. These include grippers, robot tools, inspection equipment and other parts at the end of a kinematic chain.

Extended jaw: An (optional) additional jaw situated at the end of an impactive gripper finger. It may, in preference to the finger itself, be modified to fit the profile of the object and it may be replaceable.

Gripper: The generic term for all prehension devices whether robotic or otherwise. Loosely defined in four categories: Impactive, Astrictive, Ingressive and Contigutive.

Gripper axis: A frame with its origin in the TCP (Tool Centre Point). This coordinate system is used to specify the gripper orientation. Figure 1.4 shows a gripper with three translational and three rotational degrees of freedom. The gripper frame is normally defined relative to the flange frame of the industrial robot.

Gripper changing system: A module for rapid manual, but in most cases automatic, exchange of an end-effector using a standard mechanical interface. In doing so, all power and control cables must be disconnected and reconnected.

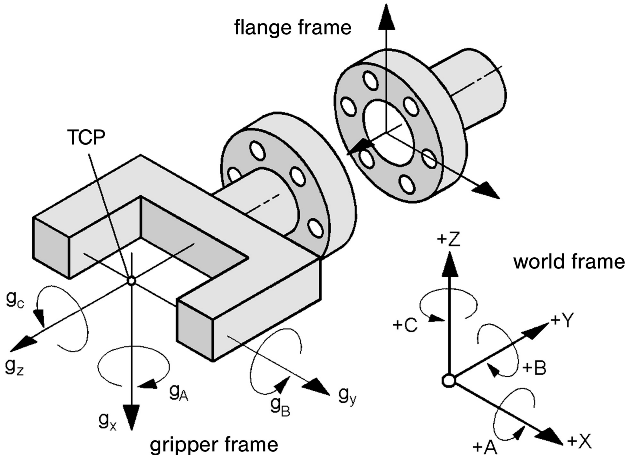


Fig. 1.4: Gripper frame

Gripper finger: Rigid, elastic, or multi-link grasping organ to enclose or clasp the object to be handled. Fingers are often equipped with extended gripper jaws at their ends. The gripper finger is usually (though not always) the active part making contact between the gripper and the object.

Gripper hand (*hand unit*): Grippers with multiple jointed fingers, each of them representing an open kinematic chain and possessing a high degree of freedom with f joints, e.g. $f = 9$.

Gripper jaw: The part of the gripper to which the fingers are normally attached. The jaw does not necessarily come into contact with the object to be gripped. Note: in some cases gripper fingers may be fitted with an additional small (extended) jaws at their ends.

Gripping area: Area of the prehension (gripper jaw) across which force is transmitted to the object surface. The larger the contact surface area of an impactive gripper, the smaller the pressure on the object surface.

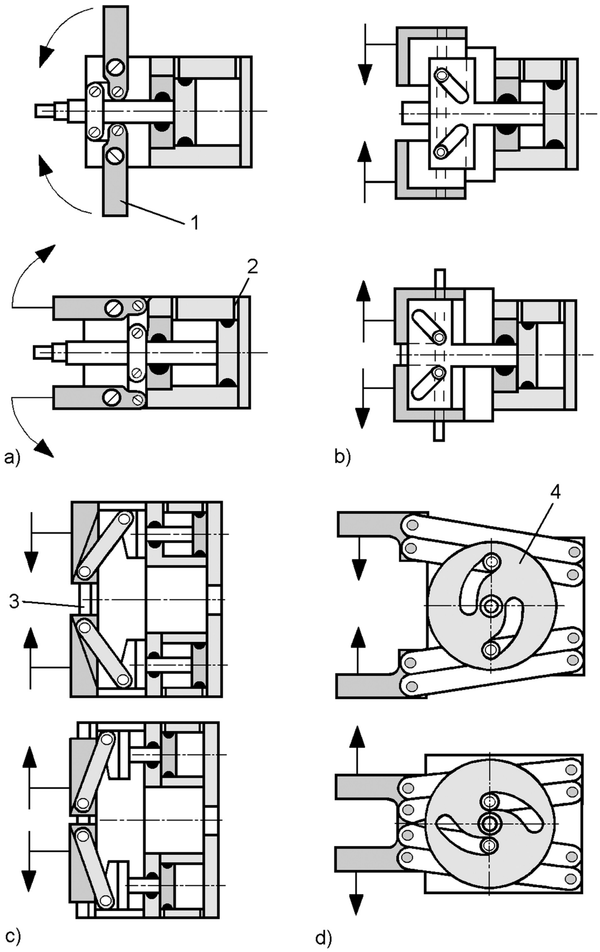
Gripping surface: The passive contact surface between object and gripper, i.e. the surface which is subjected to prehension forces.

Holding system: A term often used for an active prehension system including gripper, jaws and fingers. It may also apply to a passive temporary retaining device.

Impactive gripper: A mechanical gripper whereby prehension is achieved by impactive forces, i.e. forces which impact against the surface of the object to be acquired.

Ingressive gripper: Ingression refers to the permeation of an objects surface by the prehension means. Ingression can be intrusive (pins) or non intrusive (e.g. hook and loop).

Kinematic system: Mechanical unit (gear) converting drive motion of the prime mover into prehension action (jaw motion) with characteristic transmission rates for velocities and forces. The most often used kinematic components are lever, screw, and toggle lever gears. The gear determines the final velocity of the jaw movement, and the gripping force characteristics. Grippers without moving elements require no kinematics. Some examples of gears are shown in Figure 1.5.



1 basic jaw or finger
2 pneumatic cylinder
3 straight guideway
4 cam disk

Fig. 1.5: Pneumatically driven gripper with kinematic system for transmission of motion *(Sommer-automatic)*
a) angle gripper with toggle lever mechanics
b) parallel gripper with roller link
c) parallel gripper with two pneumatic cylinders
d) parallel gripper with cam disk

Magnetoadhesion: Prehension force by means of a magnetic field (permanent or electrically generated).

Multiple grippers: Several grippers mounted on the same substrate, intended for the simultaneously prehension of more than two objects.

Prehendability: The suitability of an object to be automatically gripped. Dependant on the surface properties, weight and strength when exposed to prehension forces. This property can sometimes be enhanced by applying such surfaces or elements (handling adapters) which are required only for a particular procedure.

Prehension: The act of acquiring an object in or onto the gripper.

Prehension planning: Deals with the problem of how to ensure stable mating between robot gripper and workpiece. A prehension strategy must be chosen in such a way that it can be accomplished in a stable manner and collision free. Post prehension misalignment of the object is undesirable. In many circumstances, special constraints must be observed in order to avoid contact with certain parts of the object (forbidden zones).

Prehension systems: Complete systems including grippers supplemented with additional units (subsystems), e.g. rotation, pivot and short-travel units, changing systems, joining (adjustment) tools, collision and overload protection mechanisms, measuring devices and other sensors.

Protection system: These are elements attached to the inner or outer part of the gripper which are activated in case of overload or collision in order to protect the robot and gripper from damage (warning signal, emergency stop activation, passive or active evasive movement).

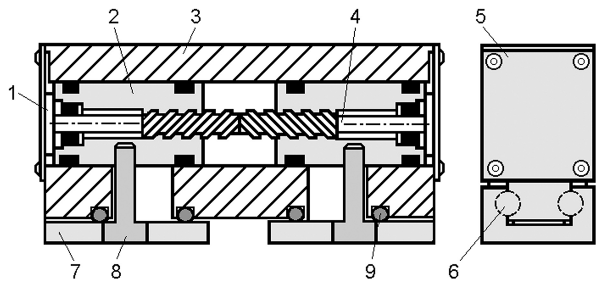
Retention: Pertains to the post prehension status of an object already held in the gripper. Note: prehension and retention forces are not always equal.

Sensor system: Sensors pertinent to the task of prehension. This may include sensors built into the end-effector, possibly with integrated data pre-processing, for position detection, registration of object approach, determination of gripping force, path and angle measurements, slippage detection etc.

Sucker: Normally refers to a passive suction element (disk, cap or cup) which does not require active vacuum suction but relies on the evacuation of air by distortion of the element against the object surface.

Suction head: A form of astrictive gripper which may consist of one or more vacuum suction elements (discs, caps or cups) freom which air is actively evacuated by means of externally generated negative pressure.

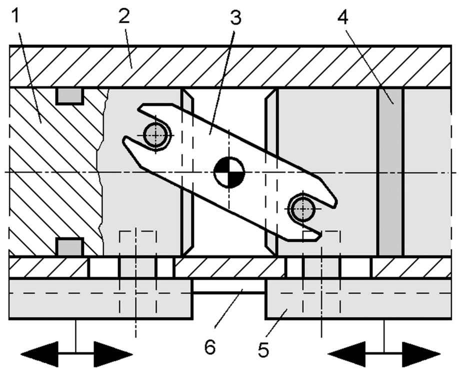
Synchronization: In the majority of 2 and 3 finger grippers it is intended that the fingers close in a uniform manner towards the centre of the gripper. In order to achieve this the motion of the fingers must be synchronized. Pneumatic cylinders, as can be seen from the example in Figure 1.6, can be moved synchronously by means of a shaft with both right and left handed threads.



1 cover plate
2 pneumatic cylinders
3 housing
4 thread shaft
5 sealing plate
6 basic jaw guides
7 basic jaws
8 securing bolts
9 seals

Fig. 1.6: Synchronization of the gripper fingers by means of a right and left hand threaded shaft

Such movement may also be realized by a gear comprising only links and levers (double swing mechanism), as shown in Figure 1.7 (see also the solution depicted later in Figure 3.15). The basic jaws are again pneumatically driven by means of cylinders integrated within the gripper housing.



1 pneumatic cylinder
2 housing or cylindrical boring
3 synchronous lever
4 sealing
5 basic jaw
6 jaw guides

Fig. 1.7: Synchronization by means of a double swing-yoke-drive (scotch-yoke drive)

TCP (*tool centre point*): Working point at the end of a kinematic chain. The TCP serves also as a programmed reference point for an end effector and as a rule determines the origin of the tool frame. A coordinate system whose origin coincides with the TCP is called *tool frame*. Multiple gripper heads may possess several TCPs (Fig. 1.8) or one main TCP with the rest being defined relative to the main TCP by tool offsets.

Thermoadhesion: Contigutive prehension force by means of thermal effects. Usually in the form of freezing or melting.

Workpiece or object: A general term which refers to the component or object to be prehended or which is already under prehension by the gripper.

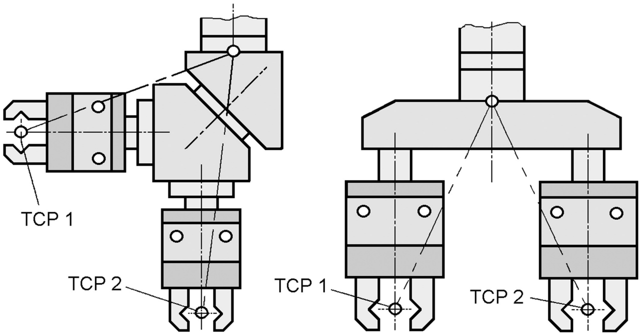


Fig. 1.8: TCPs of multiple grippers

1.3 Grasping in Natural Systems

In the course of its evolution Nature has created many different interesting grasping mechanisms. The elephant's trunk can be regarded as a biomechanical phenomenon. According to Brehm's Life of Animals, it is

"...simultaneously a smelling, feeling, and grasping organ. It is composed of ring and longitudinal muscles, according to G. Cuvier (1769–1832) these are about 40 000 separate bundles, which enable not only any twisting but also stretching and contraction".

In his work on kinematics during the second half of the 19th century, *F. Reuleaux* (1829–1905) analyzed (among others) animal mechanisms of motion [1-2]. These included the mouths of fish and bird's beaks which are also used to perform prehension tasks. The use of astrictive force though suction is also nothing new in nature. Such techniques are used by fauna as suction feet (Fig. 1.9), e.g. in cephalopods. The male of the diving beetle (*Dytiscus marginalis*) possesses stemmed suction cups on its front legs. Applying them to a surface causes spreading of the finely chitinous, semispheric caps at their delicate edges. Drawing them back then results in a reduction in pressure which in turn produces the adhesion effect. Lizards possess adhesion lamellae on their toes (dry adhesion) which enable them to traverse glass plates using their surface roughness [1-3]. There are in fact many

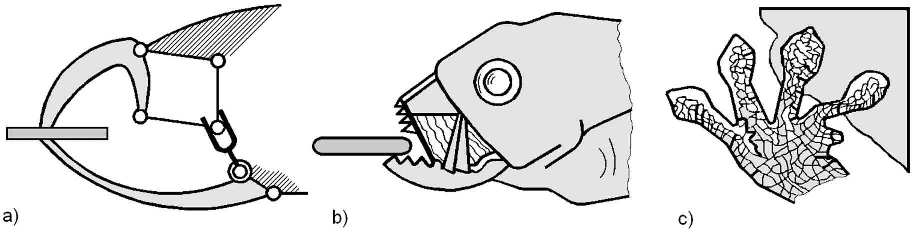


Fig. 1.9: Natural grasping, holding, and mastication mechanisms
a) bird's beak, b) fish mouth, c) suction foot

grippers whose kinematic principles are strongly related to those of Bird's beaks or ele phant's trunks, for example in paint spraying or to encompass an object (see the soft grippers in Chapters 8 and 13). In order to handle fragile objects, grippers which imitate the musculous hydrostates of squid tentacles, have been utilised. The prehension and mastication organs of insects (*Chelicerae* of spiders, *Mandibles* of biting and chewing insects like the antlions) resemble impactive grippers [1-4].

If we consider the osprey (Fig. 1.10), we can see that the problem of "grasping under complicated conditions" has been solved in the course of biological evolution in a very interesting manner. The osprey is able to grasp objects whose surfaces enjoy extremely low friction coefficients (specifically to avoid prehension by predators!) during flight.

The grasping foot exhibits long-drawn and sharp claws which make it possible to catch the prey (ingressive prehension). The lower part of the foot exhibits soft pads with a high coefficient of friction (buffered impactive prehension). During grasping these pads produce a suction (astrictive prehension) effect against the smooth surface of the object. Hence, in this case several effective prehension principles are combined. Indeed, there also exist robot grippers which prehend by impactive clamping and simultaneously use vacuum suction (Fig. 1.10b). However, none of the man made grippers possess the wealth of fine details observed in nature. Why?

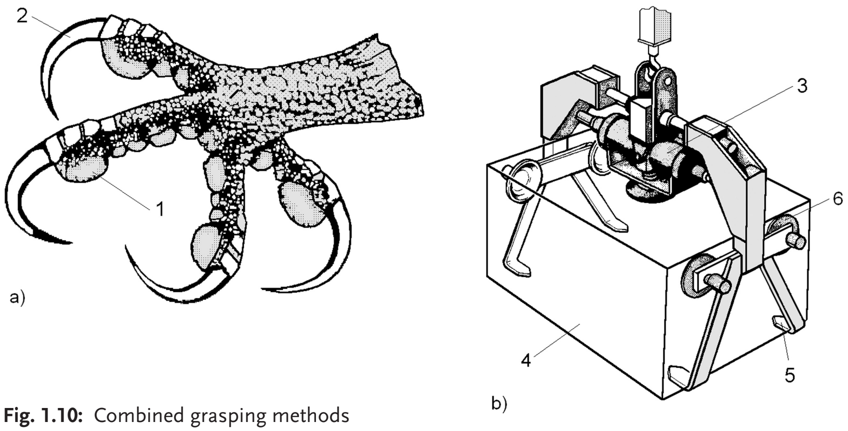


Fig. 1.10: Combined grasping methods
a) grasping foot of an osprey Pandion haliaetus, b) hook gripper combined with suction cups
1 anti slip pads, 2 claw, 3 pneumatic cylinder, 4 gripped object, 5 hook, 6 suction cup

Crab pincers are another good example often imitated by man. The crab arms end with a robust scissor mechanism which serves for both grasping and pressing. From the point of view of kinematics, it is simply a matter of the successive coupling of two four-link spherical gears (Fig. 1.11). To these ends crab arms possess the following design properties:

- They have a large pivoting angle for a small number of arm links.
- They can exert relatively large forces.
- The joints between the arm links are free from mechanical play and are capable of working under pressure over an extended range of motion.

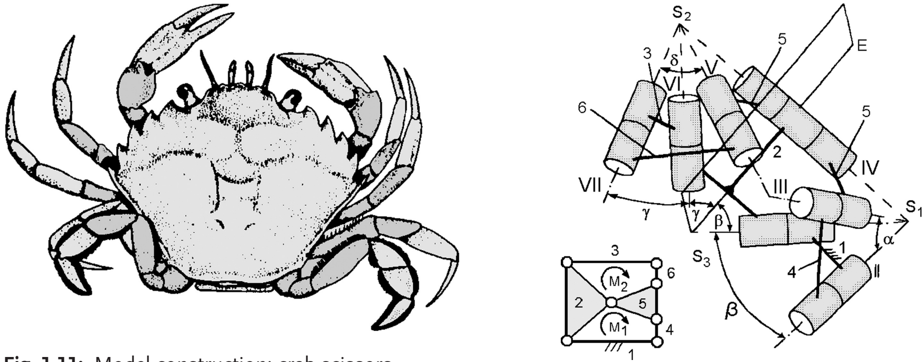


Fig. 1.11: Model construction: crab scissors
left: crab; right: kinematic scheme (four-joint chain) after [1-5];
1 frame, 2 interlink, 3 link, 4 drive swing, 5 coupler

The crab has developed an ingenious solution to the articulation between arm members. It is based on two spherical joints of polar cap form housed concentrically within one another. These spherical joints consist in turn of several additional shells whose surfaces serve as slip and contact areas. Such joints are of special interest for miniaturized mechanisms since joint solutions of the “fork head – pin” type cannot be arbitrarily downscaled.

Ball-and-socket (spherical) joints in living organisms are often coated with a jelly-like substance as a lubricant so that the connection is free from play and smooth running. In addition it may exhibit nonlinearities (stick-slip) effects.

The famous Greek philosopher Aristotele (384-322 BC) described the hands as “the tool of all tools”. The 5-finger human hands represent a particularly flexible and useful grasping organ, particularly in conjunction with control though eye-hand feedback.

The bones of the hand are anatomically divided into three groups: the wrist or carpal bones (16 small bones at the root of the hand); the midhand or palm bones, and the first link (metacarpus) and finger (phalanx) bones (Fig. 1.12).

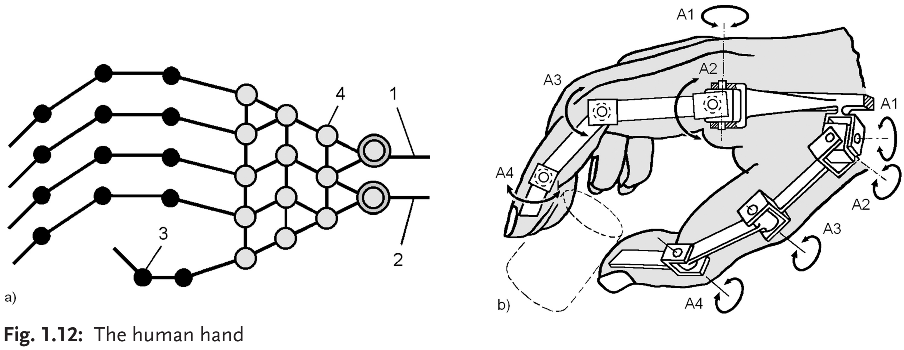
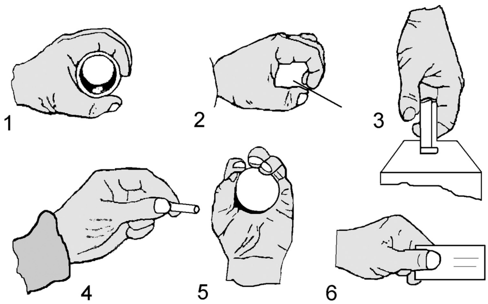


Fig. 1.12: The human hand
a) mechanical joint system [1-6], b) simplified mechanical representation.
1 radius, 2 ulna, 3 finger joint, 4 hand joint, A rotation axis

There are 8 carpal bones, 5 midhand bones (one for each finger), and 14 links (two for the thumb and three for every other finger). This anatomic constellation enables a total of 22 degrees of freedom in which as many as 48 muscles are involved.

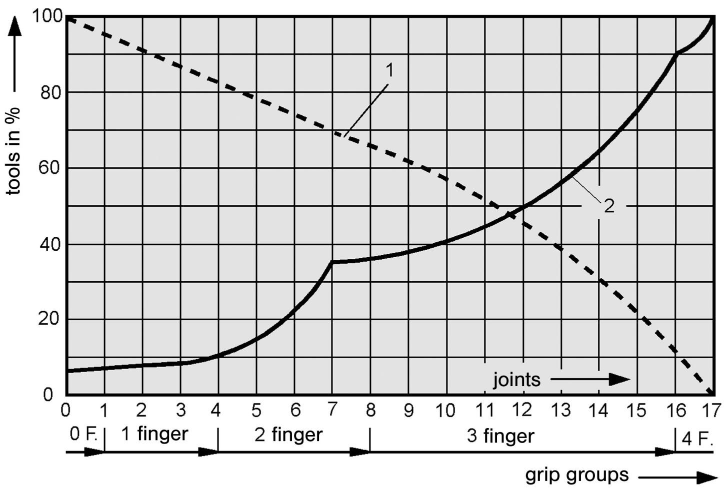
The hand and forearm muscles are involved in practicing, memorizing, retrieval, and variation in a tremendous number of separate grips. The human hand possesses ultimately 27 degrees of freedom. The exact number depends on how the muscles are classified in independent groups [1-7]. If the finely coordinated muscles are independently moved and one defines for each degree of freedom the two end and one mid positions, this alone will give 3^{27}, i.e. more than 7 billion different potential hand positions. Typical hand grips can be grouped, more or less exhaustively, into six grip classes (Fig. 1.13) [1-8 to 1-10].



1 cylindrical hollow grip
2 tip grip
3 hook grip
4 three finger grip
5 hand palm grip
6 tong grip

Fig. 1.13: The different hand grip classes

If the consideration is restricted to human activities necessary for industrial work, a direct relationship between the hand with the necessary tools and the number of fingers involved in the specific work may be observed. In other words, fingers can be replaced by tools. This relationship is illustrated in Figure 1.14.



1 number of tools
2 grip possibilities

Fig. 1.14: Fingers can be replaced by tools [1-11]

Zero fingers in the graph should be understood as movement of the arm joints only. As can be seen, the addition of the fifth finger makes negligible contribution to industrial work. About 90% of the grips involved in industrial applications can be realized with a three finger hand. Furthermore, all fingers do not possess the same strength. The middle finger is the strongest one and the little finger the weakest. The strength potential is distributed as follows: index finger 21%, middle finger 34%, ring finger 27%, and little finger 18%.

Grasping operations are always an integral part of more complicated handling strategies even in cases when they are performed automatically. Consequently, grippers should always be considered and evaluated for each individual case. As for the assembling of components, a brief procedure is shown in Figure 1.15, whereby the simple loading of a clamping device can be considered to be equivalent to the final assembly step.

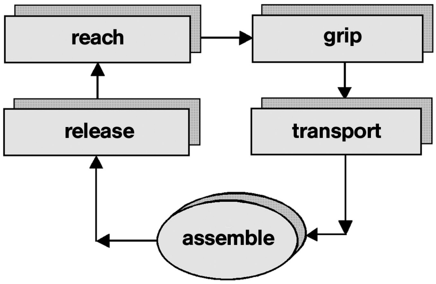


Fig. 1.15: General flow-chart of an assembly cycle [1-12]

1.4 Historical Overview of Technical Hands

The first analogies of the human hand were developed as artificial replacements: The "iron fist" of *Götz von Berlichingen* (1480–1562) possessed five separate fingers (Fig. 1.16).

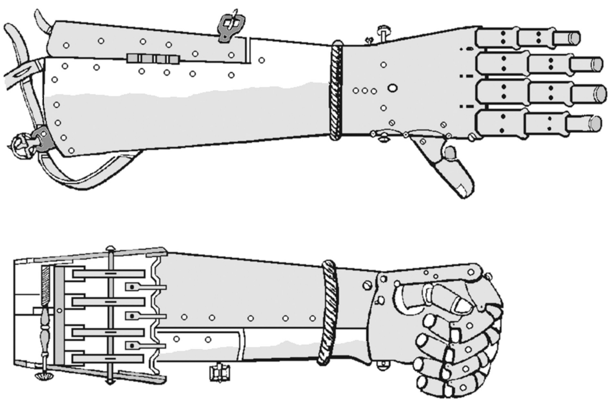


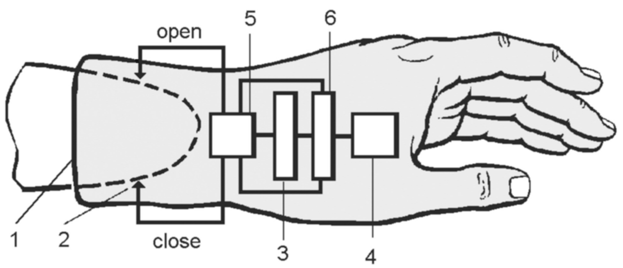
Fig. 1.16: The iron first of *Götz von Berlichingen*, knight of the Frankish Kingdom

The fingers could be passively bent, fixed and released at the push of a button. Although the hand weighs about 1.5 kg this was not considered particularly heavy for those times.

In 1564 the French physician *Ambroise Paré* (1510 – 1590) designed a mechanical hand, in which the separate fingers were equipped with individual mechanics. At that time the idea caused a sensation because it seemed to demonstrate that humans and machines operate in the same manner and there are possibly spheres where they are exchangeable [1-13].

As a result of World War I the demand for hand replacements increased. The first hand replacement driven by external energy was designed by *E. F. Sauerbruch* (1875 – 1951) and appeared in 1916. He utilized the remaining available force of the residual muscles in the amputation stump. The muscle movement was transmitted to the replacement mechanics by inserted ivory pivot pins [1-14].

The first successful use of arm stump bio-currents to control a miniaturized electromechanical system in a replacement hand was made in 1947. In the meantime such so called bio-hands are readily available and their carrying capability and functionality are comparatively good. The basic principle of operation is shown in Figure 1.17. The electromotoric *Vaduz-hand* of the Swiss *E. Wilms* (1949) had a similar construction.

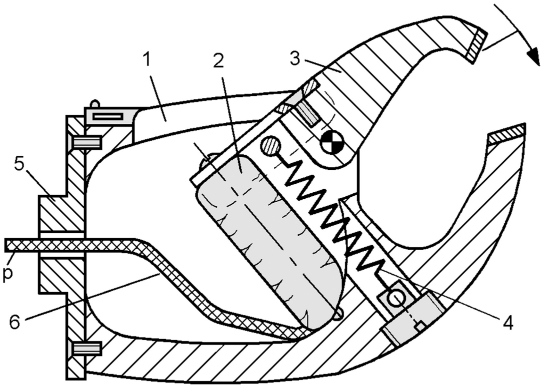


1 arm stump
2 skin electrodes
3 battery
4 gear
5 amplifier
6 motor

Fig. 1.17: Construction of a myoelectric biohand (prosthesis)

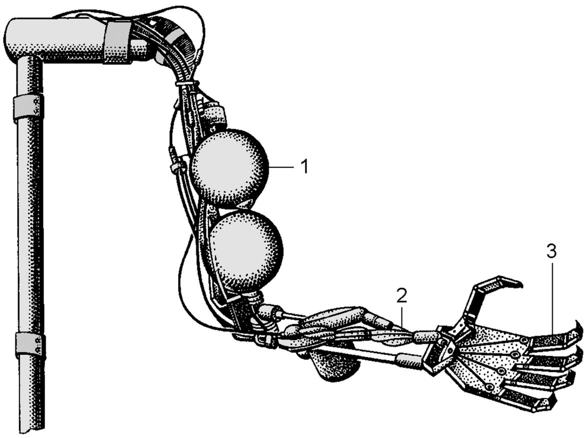
In addition to electromechanical systems, pneumatic actuation has also been used for hand replacements. Some 60 years ago an arm prosthesis driven by compressed air was developed at the orthopaedic centre in Heidelberg (Germany). The hand prosthesis depicted in Figure 1.18 is a part of it. The fluid actuator is a flexible extensible body which, when inflated, pivots the finger into a firm grip. A return spring serves to release it. Until 1965 more that 350 patients benefited from this design. The so-called *McKibben* arm exhibits similar characteristics.

In the 1950s the American *J. L. McKibben* designed a pneumatic muscle intended for prosthetic actuation (Fig. 1.19). The muscle consisted of a rubber tube with a net of inelastic threads in rhomboid pattern over, and along the length, of the surface. When pressurized the muscle inflates and simultaneously shortens. Wires transmit these length changes to the joints which in turn produce motion in the finger links. The operation of the fluid muscle as a gripper actuator is illustrated in Figure 3.15. Unfortunately, such a fluid muscle can produce only contraction forces.



1 gripper housing
2 flexible pneumatic actuator
3 wooden finger
5 fitting flange
4 return spring
6 compressed air tube
p compressed air input

Fig. 1.18: Hand prosthesis from the orthopaedic center in Heidelberg (1948)



1 rubber muscle
2 wire and wire lead
3 hand prosthesis

Fig. 1.19: Arm prosthesis with segmented rubber muscles (after *McKibben*, USA)

Another trend relates to the so-called android hands developed for special figures intended for exposition. The automats designed by *Pierre Jaquet Droz* (1721 – 1790), *Henri-Louis Jaquet Droz* (1752 – 1838) and the mechanic *Jean Frederic de Leschot* (1747 – 1824) are famous androids which caused sensations in their times [1-15]. The figures were equipped with program control (turn controller). Figure 1.20 shows the hand mechanics of one such figure.

All these, however, did not stimulate the development of robotics. Their designs contained few functioning parts and served basically to optically imitate the human hands. This said, the “flutist”, a “saloon robot” for the exhibit of *J. de Vaucanson* (1709 – 1782), actually used leather holstered fingers whilst playing the flute.

The artificial hands needed today for robots and remote-controlled manipulators are substantially different. A robot hand with skilful fingers is the realization of the ancient

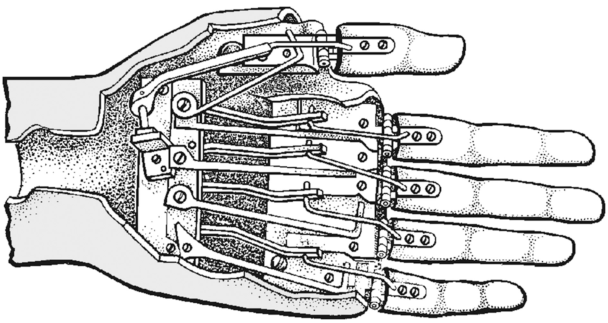


Fig. 1.20: Hand mechanics of a female "musician", an android playing harpsichord (designed by *Jaquet-Droz* [father & son] and *J.-F. Leschot*, 1774)

dream to provide machines with human abilities. The first technical hands for automation and research were developed in the 1960s. The robot hands known from such research are usually named after their institution or its place of origin, e.g., Belgrade/USC Hand, Darmstadt Hand, DLR Hand, Rhode Island Hand (for cylindrical components), Hitachi Hand, Karlsruhe Hand, Odetics Hand, Rosheim Hand, SRC Hand, Stanford/JPL Hand, Utah/ MIT Hand, and Victory-Enterprises Hand. Most of these hands are driven by electric motors. The wiring and coupling of actuator motion, mostly by means of chords, is a serious problem related to producing adequate force in the available space. A full description of dextrous hands is given in Chapter 8.