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Excerpt
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Part I

Methodology

1

Analysis of grip forces during object manipulation

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Summary

With the invention of strain gauges, isometric finger forces such as those produced during grasping an object could be measured continuously, precisely and without major constraints to the grip. In the precision grip between thumb and index finger, elementary performance aspects such as maximum grip force, ability to maintain a constant force, fast force changes or tracking of a dynamic target have been studied. In 1984, Johansson and Westling presented their paradigm based on the measurement of grip and load forces during grasping and lifting of an object. Their studies inspired a great deal of scientific interest in this aspect of fine motor control examined in healthy subjects as well as in patients with peripheral or central nervous system diseases. Research in this field progressed by introducing other motor tasks with specific demands on the control system, such as the compensation of inertial forces during movements of grasped objects. In addition, methods improved by technical developments such as 6-degree-of-freedom force/torque sensors, autonomous measurement devices, or force matrices to measure pressure distributions at grasping surfaces. Thus, measurements of isometric grip forces during object manipulation became a widely used method in neurophysiological and clinical motor sciences.

Control of isometric grip forces

Historically, the typical way to measure the force generated by the fingers or the whole hand was via compression of springs (e.g. Du Mensil de Rochemont, 1926). In addition, objects with known weights were used to load the hand or the fingers with a defined force (Truschel, 1913). With the invention of strain gauges in 1938, direct, practically isometric measurements of applied force became possible. Strain gauges change their electrical resistance during very small deformations in the range of hundredths of a millimeter. By fixing strain gauges on to elastic carriers such as metal beams and by using a special electrical circuit (Wheatstone Bridge) with differential electrical amplification, a voltage or current signal is generated that gives an immediate and continuous read-out of the applied force. Strain gauges, either on metallic or on silicon bases, still constitute the standard technique for continuous force measurements. Other electronic methods are based on piezoelectric,

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capacitive or optical principles. Still, forces can be measured without electronics by pure mechanical or hydraulic devices.

In a series of articles, Ghez and Gordon argued that the study of isometric force pulses avoids many of the problems associated with study of movements (Ghez & Gordon, 1987; Gordon & Ghez, 1987a, b). Thus, joint movements induce complex shifts of internal and external forces, for example by changing lever arms and corresponding torques. In addition, stretch reflexes may arise during movements and interfere with the effects of the central command. Finally, the relationship between electromyographic (EMG) signals and movement is complex and not uniquely determined (Ghez & Gordon, 1987). The authors showed that isometric force pulses produced by the elbow were isochronous, the rise time being independent from the force amplitude, even when accurate responses were required (Gordon & Ghez, 1987a; see also Freund & Büdingen, 1978). Many other studies employed paradigms with isometric force production by the arm, hand or fingers to study the principles of motor programming (e.g. Ulrich *et al*., 1995) or the psychophysics of force perception, discrimination or matching (Stevens & Mack, 1959; Phillips, 1986).

Grasping an object between the pads of the thumb and the index finger has been considered as the prototype grip used for precision handling. This precision grip can be contrasted with a power grip that provides maximal contact of the palmar surfaces of fingers and hand with the manipulated object enabling transmission of high forces (Napier, 1956; Cutkosky & Howe, 1990). Both grip types have been subjected to numerous measurements of the produced grip force.

Power grip is primarily studied if the aim is to obtain a measure of maximum strength. Various devices have been developed to measure maximum force in a whole hand power grip. The most widely used clinical device is probably the Jamar Hand Dynamometer that measures strength with a hydraulic method and ergonomically formed handles (Mathiowetz *et al*., 1985; Harth & Vetter, 1994). Normative data are available (Harth & Vetter, 1994; Hanten *et al*., 1999) and the value of strength measurements in clinical disciplines like orthopedics and neurology is beyond doubt (Fees, 1986; Bohannon, 1989; Boissy *et al*., 1999). Nevertheless caution was expressed against an over-generalization of strength measures in the context of neurological diseases (Bohannon, 1989; Jones, 1989; Hermsdörfer & Mai, 1996).

Maximum grip force may also be measured with a precision grip (Harth & Vetter, 1994; MacDermid *et al*., 2001); however, more typically the precision grip is studied with an aim to examine the type of forces (usually well below the level of the subject's maximum strength) which are used when manipulating everyday-life objects. Thus, the relationship between the activity of hand and finger muscles contributing to a precision grip between thumb and index finger and the resulting grip force was established. A refined study of the EMG activity of 15 finger muscles detected correlations with low grip forces in the range between 1 and 3 N in ten muscles (Maier & Hepp-Reymond, 1995). In particular, intrinsic finger muscles showed a high correlation, extrinsic finger flexor muscles a moderate correlation, and extrinsic extensor muscles no correlation with low precision grip forces (see also Chapter 5). The relationship between grip force in a precision grip and cerebral activity was investigated in single cell recordings in monkeys and in neuroimaging studies of human subjects. In general, these studies showed a particularly strong relationship between the produced force and neural activity in the primary motor cortex, but also in the supplementary motor area and the premotor cortex (Hepp-Reymond *et al*., 1978; Ashe, 1997; Cadoret & Smith, 1997; Cramer *et al*., 2002; see Chapters 4 and 7).

Apart from relationships between force and neurophysiological parameters, specific aspects of force control have been investigated in clinical studies. For example, a motor task during which grip force had to be increased and decreased as fast as possible was tested in different groups of brain-damaged patients. These fast force changes proved highly sensitive to differentiate patients from healthy subjects and exhibited characteristic differences between hemiparetic and cerebellar patients (Avarello *et al*., 1988; Mai *et al*., 1988; Hermsdörfer *et al*., 2003).

Another important aspect of grip force control is the ability to maintain a constant force. This was tested by providing a visual feedback of the produced force on a monitor (e.g. a vertical bar with force-linear length) and indicating a constant target force (e.g. a horizontal line). To study the role of visual control, feedback could be withdrawn. For this task, developmental effects were demonstrated in young children (Blank *et al*., 1999) and decline with age was shown in elderly subjects (Vaillancourt *et al*., 2003). In addition, deficits of constant grip force production were observed in different neurological patients such as patients with Parkinson's disease (Vaillancourt *et al*., 2001), cerebellar patients (Mai *et al*., 1988), or patients with somatosensory deafferentation (Rothwell *et al*., 1982; see Chapter 19).

In addition, the ability to adapt the grip force to changing levels in the target force was examined. Such tracking tasks classically tested movements rather than forces with the aim to reveal the input–output characteristics of the human sensorimotor system (e.g. Navas & Stark, 1968; Miall *et al*., 1985). When used to study the control of grip forces, one cursor on a computer screen typically represents the level of the target force and another cursor shows the currently produced grip force. Comparable to constant force production, tracking studies using isometric grip force as a feedback signal revealed effects of development (Blank *et al*., 2000) and aging (Lazarus & Haynes, 1997). A trapezoid target signal was used in a study of motor training in stroke patients (Kriz *et al*., 1995; see Chapter 29). Patients successfully decreased overshoots und undershoots of grip force during repeated tracking of the slow target.

Figure 1.1 compares some of these aspects of grip force control in three selected patients. The patients exhibit clear differences in performance across the different tasks. While patient Pat1 shows normal ability to maintain a constant force and to track a moving target, force changes were slowed and of small amplitude, and strength was reduced to 40% of the non-paretic hand. Patient Pat2 exhibited a nearly opposite pattern. His grip force was highly irregular during constant force production and even more irregular during tracking; however he performed force changes at a relatively high frequency and maximum force was in the lower range of his age group. Finally, patient Pat3 presented with sporadic force oscillations

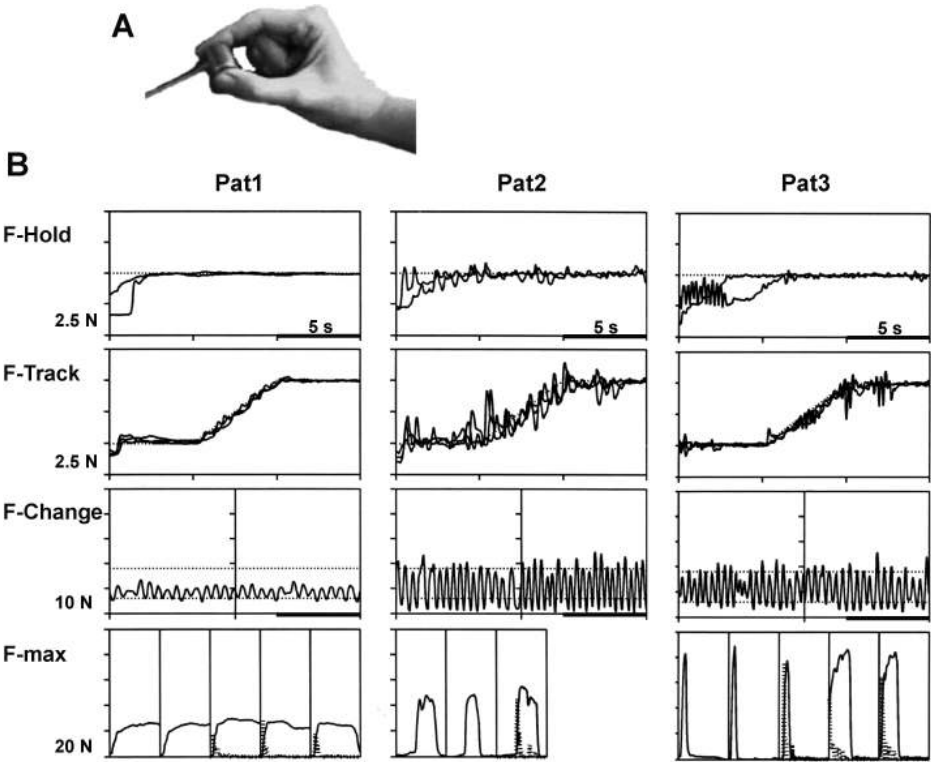

Figure 1.1. A. Force sensor grasped in a precision grip. B. Grip force of three patients with cerebral lesions (Pat1: infarction of medial cerebral artery; Pat2: hemorrhages in the brain stem; Pat3: head injury) in four tasks of isometric grip force control. F-Hold: maintenance of a low constant force; F-Track: tracking of a ramp-like increase of target force; F-Change: changes of grip force at maximum frequency; F-max: strength of precision grip. Only the impaired hand is shown. Modified from Hermsdörfer & Mai (1996).

during the precision tasks, a moderate slowing of force changes but high strength values (Hermsdörfer & Mai, 1996).

Grip forces during grasping and lifting of objects

In 1984 Johansson and Westling published their ingenious paradigm to study the control of grip force under natural conditions, namely the grasping and lifting of objects (Johansson & Westling, 1984; see Chapter 11). Figure 1.2 shows the device they developed for that purpose. The device is grasped with a precision grip between thumb and index finger at two disks. Appropriately mounted strain gauges measure the grip force and the load force. Note that at the beginning while the object is firmly on the ground load force is zero, it increases with a muscular activity that produces an upward lifting force, and equals the

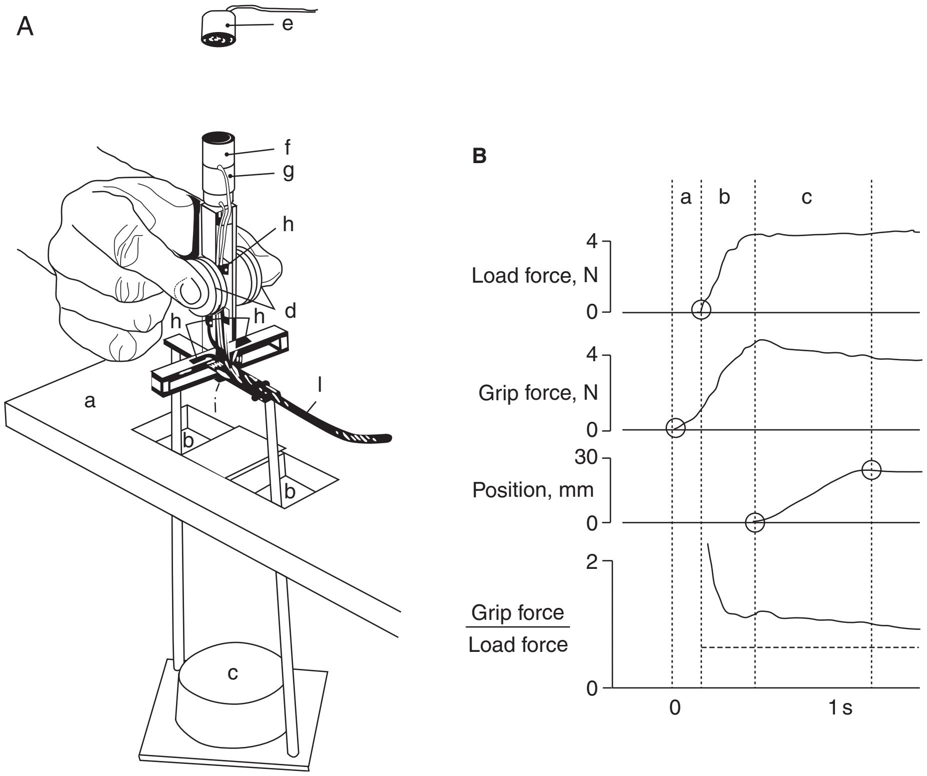

Figure 1.2. A. Device developed by Johansson and Westling to measure grip and load forces during grasping and lifting. The device is grasped with thumb and index finger at exchangeable disks (d), below which strain gauges are mounted to measure the grip forces of both fingers and the vertical load force (lifting force) (h). Additional sensors measure vertical acceleration (g) and position (lifting height) (f, e). The weight (c) can be exchanged. B. Load force, grip force, position and ratio between grip and load force during one typical grasping and lifting movement. The horizontal line in the grip force/load force diagram indicates the slip ratio (slip force related to load force). Time intervals a, b and c indicate the preload phase, the loading phase and the lifting (transitional) phase; from Johansson & Westling (1984).

weight of the device at the moment of lift-off. Then the load remains equal to the weight apart from possible inertial components due to acceleration. During stationary holding the grip forces of thumb and index finger are identical.

Most importantly, the grip force is not defined and can take any magnitude as long as it is higher than a certain minimum (slip force) to avoid slippage of the device (see Chapters 3 and 11). Thus the grip force could theoretically be established before any lifting force is produced and could be largely independent from the weight of the device. The study of grip force during lifting therefore reveals the response of the nervous system to the physical constraints defined by the task. Figure 1.2B demonstrates the most important characteristics of grip force control in this situation. At time zero the fingers contact the disks and grip force increases. After just a small increase of the grip force, the load force starts to increase as well. Both forces then increase until a change in the position signal indicates lift-off. The object is then lifted to the final height with a near-constant load (equalling weight) and a slight relaxation of grip force. The horizontal line in the grip force versus load force diagram indicates the minimum ratio necessary to prevent slipping of the object. It is obvious that grip force exerted when holding the object is only a bit higher than this minimum. The close temporal coupling between the grip and the load force and the precise scaling of the grip force to the load are characteristics of physiological grip-force control during grasping and lifting of objects. Thus, contrary to the theoretically possible control mode mentioned at the beginning of the paragraph, the system works highly economically and anticipates precisely the physical demands of the task (Johansson & Westling, 1984).

By exchanging the weight below the table (see Figure 1.2A) the weight of the whole device was varied experimentally. It was shown that grip forces are adjusted to the different weights (defining the load forces) with a nearly constant ratio between the grip force and the load force (Johansson & Westling, 1984; Westling & Johansson, 1984). Changing the surface material by exchanging the disks caused variations of the friction between fingers and object and resulted in different minimal grip forces required to prevent slippage of the object (Johansson & Westling, 1984; Westling & Johansson, 1984) (for the measurement of the coefficient of friction, see also Chapter 3). Grip forces were higher for more slippery surfaces with lower friction (e.g. silk) as opposed to materials with higher friction (e.g. sandpaper). Another relevant factor is the shape of the grasped surface. Experiments with changes of the inclination of the grip surface revealed increased grip force for more "Λ"-shaped test objects as opposed to lower grip force for "V"-shaped objects (Jenmalm & Johansson, 1997). In contrast, variation of curvature (convex versus concave with different radii) influenced the grip force only inconsistently (Jenmalm *et al*., 1998).

In their experiments, Johansson and colleagues also investigated the effects of perturbations on the control of grasping and lifting. A clever and simple paradigm enabled the direct comparison between the effects of unpredictable and predictable perturbations (Johansson & Westling, 1988). The subject held the device stationary with eyes closed and a small mass was thrown from a defined height into a container fastened underneath the device. The mass was either released by the examiner at unpredictable time points, or it was released by the subject from the other hand. While in the unpredictable condition, grip force lagged the sudden load increase by latencies starting from 70 ms, anticipatory increases of the grip force were already obvious before impact when the mass was released by the subject (Turrell *et al*., 1999; Delevoye-Turrell *et al*., 2003; Nowak & Hermsdörfer, 2004). This shows how effectively sensory information is used in the control of grip force but also how effectively the control strategies are adapted to the demands of the task (Johansson, 1996; Flanagan & Johansson, 2002). A more thorough account of the control of grip forces in object grasping and lifting, with a particular emphasis on the sensory control mechanisms involved, is provided in Chapter 11.

Grasping–lifting paradigms, based on the methods developed by Johansson and colleagues, were used in numerous studies of human grasping and lifting such as studies on development (Forssberg *et al*., 1991, 1992; Gordon *et al*., 1992; see Chapter 17), on aging (Cole *et al*., 1999; see Chapter 18), and on the effects of temporary sensory disturbances in healthy subjects (Johansson & Westling, 1984; Jenmalm & Johansson, 1997; Monzee *et al*., 2003; see Chapter 19). The effects of nervous system damage on this task were investigated in various populations of patients with neurological diseases such as stroke (Hermsdörfer *et al*., 2003; Wenzelburger *et al*., 2005; Raghavan *et al*., 2006; see Chapter 21), Parkinson's disease (Gordon *et al*., 1997; Fellows *et al*., 1998; Wenzelburger *et al*., 2002; see Chapters 22 and 32), Huntington's disease (Gordon *et al*., 2000; Schwarz *et al*., 2001; see Chapter 23), cerebellar diseases (Müller & Dichgans, 1994; Fellows *et al*., 2001; Nowak *et al*., 2005; see Chapter 26), traumatic brain injury (see Chapter 24) or cerebral palsy (Eliasson *et al*., 1992; Forssberg *et al*., 1999; Gordon & Duff, 1999; Duque *et al*., 2003; see Chapter 31).

One important methodological improvement for some research questions was achieved by 6-degrees-of-freedom force/torque sensors. These sensors measure the forces in the three spatial dimensions and the torques around the three spatial axes. This is technically achieved by a refined placing of the strain gauges on a specially designed metal frame. Cross-talk between the different channels is compensated by a controller device. Six-degrees-of-freedom sensors with an appropriate force range are available with relatively small dimensions and low weight (e.g. Nano 17, ATI Industrial Automation, 17 × 15 mm, 9 g). In addition to the measurement of the vertical load force and the orthogonal grip force (see the device in Figure 1.2A), these sensors would be capable of measuring the horizontal force which is tangential to the grip surfaces, the torque that would result from a sideward or forward–backward tilt of the whole device, and the torque that would result from an attempt to rotate the device around the vertical axis against a resistance (see also Chapter 3).

During the experimental condition depicted in Figure 1.2, the extra forces and torques will typically be small compared with the measured vertical load force and grip force. However, the execution may be less controlled when, for example, patients with movement disorders are tested. Torque can also be an experimental variable. For example, the torque during holding an object was varied by changing the horizontal distance of an extra weight connected to the grasping surface (Kinoshita *et al*., 1997). The study showed that the torque was compensated by increased grip forces, and there was a linear relationship between both signals (see also Zatsiorsky *et al*., 2003 and Chapter 3). In addition, measurements of torque allow calculation of the precision of grasping. If grip force is applied against a disk like the one depicted in Figure 1.2A and the point of force application is away from the center of the disks, torques arise. Measuring the torque and the grip force enables the calculation of the distance between finger contact and disk center (e.g. Monzee *et al*., 2003; see also Chapter 3).

Grip forces during object movements

If we move a grasped object, inertial forces arise from the acceleration of the mass. These forces are in addition to the load resulting from the object's weight and have to be compensated by the applied grip force. Figure 1.3A shows schematically the resulting load from the vectorial summation of the load components due to weight and inertia during a discrete and a continuous vertical up-and-down movement with a grasped object. During the acceleration at the beginning of a vertical upward movement, weight and inertial loads are both downward-directed and add, while during deceleration near the end of the upward movement the inertia is upward-directed so that both loads subtract. During a vertical downward movement the sequence is reversed so that the movement starts with a low total load and ends with a high total load. As opposed to discrete movements with zero loads at the lower and upper stops, accelerations are maximal at the reversal points of continuous cyclic movements. In this condition the summation and subtraction of the load components due to weight and inertia result in maximum loads at the lower turning point and smaller loads at the upper turning point (see Figure 1.3A).

Flanagan, Wing and colleagues published the first detailed descriptions of force control during movements of a grasped object (Flanagan & Wing, 1993, 1995; Flanagan & Tresilian, 1994). Figure 1.3B shows recordings of the grip force during vertical movements that represent the typical findings in healthy subjects. In both conditions, the grip force varies in close synchrony with the load. This is mainly obvious by the timing of the grip force peaks which occur nearly simultaneously with the peaks in the load force. It has to be noted that grip force and load force are typically produced by different muscle synergies; synchronicity therefore is not a biomechanical effect, but results from a feedforward-control mode (Flanagan & Tresilian, 1994; Wolpert & Flanagan, 2001; Hermsdörfer *et al*., 2004). However, grip force does not slavishly follow every load change, as is obvious from the decrease of the load force to zero at the beginning of the downward acceleration that is associated with only a small dip in the grip force trace. In close correspondence to the findings during grasping and lifting, the studies of object movement with dynamic inertial loads proved the high economy and temporal precision of the anticipation of the grip force to physical loads.

In healthy subjects, the adaptation of movement-related grip-force control to environmental perturbations was studied with various paradigms such as artificial load properties (Flanagan & Wing, 1997; Flanagan *et al*., 2003), microgravity (Hermsdörfer *et al*., 2000; Augurelle *et al*., 2003), or Coriolis forces (Nowak *et al*., 2004b). The effect of changed somatosensory afferents was investigated in healthy subjects during anesthesia of the hand, during hand cooling, or during nerve compression (Nowak *et al*., 2001; Augurelle *et al*., 2003; Cole *et al*., 2003; Nowak & Hermsdörfer, 2003a; see Chapter 19). In patients with nervous system damage, various degrees of somatosensory disturbances were studied (Nowak & Hermsdörfer, 2003b; Nowak *et al*., 2004a; see Chapter 19). Comparable to the grasping and lifting task, the paradigm was used to study grip-force anticipation in different populations of patients with brain damage such as stroke (Hermsdörfer *et al*., 2003; Nowak *et al*., 2003; see Chapter 21), cerebellar diseases (Nowak *et al*., 2002; Rost *et al*., 2005; see Chapter 26), or Parkinson's disease (Nowak & Hermsdörfer, 2002).

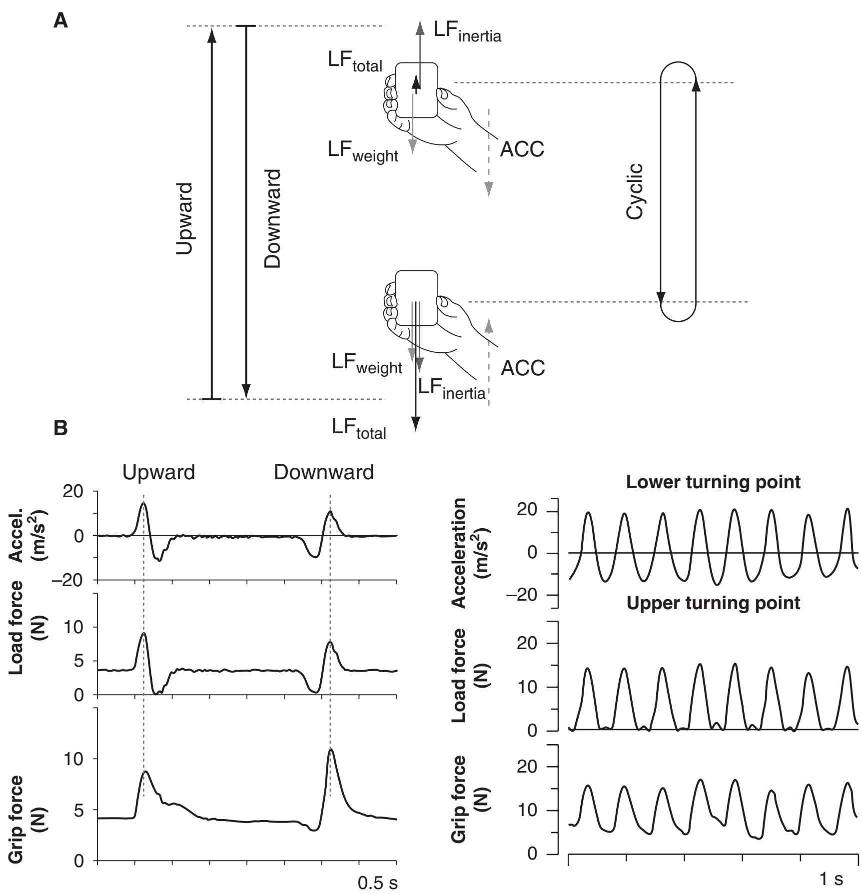

Figure 1.3. A. Illustration of the vectorial summation of the different load components during vertical movements of a grasped object. LF_{weight}: gravitational load (mass × gravity), ACC: vertical acceleration, $LF_{inertia}$: inertial load (mass × ACC), LF_{total}: total load (LF_{weight} + $LF_{inertia}$). Note that this illustration is restricted to vertical movements. When additional horizontal load components occur, particularly the component acting tangential to the grasping surface has to be considered in the calculation of the total load. B. Vertical acceleration of the object, total load force, and grip force during a single upward- and downward-directed movement (left side) and during continuous cyclic movements (right side) of a grasped object by a healthy subject.

Measurement of grip and load forces during object movements with standard equipment is usually hampered by a cable that connects the sensors with the electronics. In addition, for measurements outside the lab, in special environments, or for bedside clinical examinations, equipment is desirable that is easy to use, is quickly set up and contains only one or two units. For that purpose an autonomous instrumented manipulandum was developed (Philipp, 1999; Hermsdörfer *et al*., 2003; Nowak & Hermsdörfer, 2005, 2006). The manipulandum has a cylindrical shape with a diameter of 9 cm, a width of 4 cm, and a mass of